Universidade de Aveiro Departamento de Engenharia Mecânica
Ano 2012

Jorge Machado Rios

Temperature/Motion Feedback Loop for Fast Firing

Sinterização por Aquecimento Rápido com *Loop* Temperatura/Posição

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação científica do Doutor Duncan Paul Fagg, Investigador Auxiliar do Centro de Tecnologia Mecânica e Automação (TEMA) do Departamento de Engenharia Mecânica da Universidade de Aveiro.

o júri / the jury

presidente / president

Prof.ª Doutora Mónica Sandra Abrantes de Oliveira Correia

Professora Auxiliar da Universidade de Aveiro

Prof. Doutor Hernâni Miguel Reis Lopes

Professor Auxiliar do Departamento de Engenharia Mecânica Aplicada da Escola Superior de Tecnologia e Gestão do Instituto Politécnico de Bragança.

Doutor Duncan Paul Fagg

Equiparado a Investigador Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro

Doutor José Torres

Equiparado a Investigador Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro

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palavras-chave

Densificação, Sinterização, Aquecimento Rápido, Taxa de Rampa, *Feedback* de posição, Controlo dinâmico

.

resumo

Durante a sinterização de sistemas policristalinos ocorrem processos às partículas do material entre os quais densificação, engrossamento do grão, controlo da porosidade, segregação das partículas entre outros. Estes processos resultam num de três transportes de mecanismos condensação/evaporação na superfície, pela difusão nos limites do grão e pela difusão da látice. A microestrutura final pode ser modificada ao forçar um específico fenómeno a ser predominante sobre os restantes durante o processo de sinterização.

Por exemplo, o processo de sinterização por aquecimento rápido representa um procedimento onde o perfil Temperatura-Tempo (T-t) é alterado rapidamente para atingir uma Temperatura (T) onde a densificação predominante sobre o crescimento do grão. Desta maneira é possível obter um tamanho de grão mínimo mantendo no entanto um grau de densificação elevado em materiais policristalinos. O trabalho aqui apresentado irá projectar e construir um dispositivo mecânico que permita introduzir amostras cerâmicas dentro de um forno com uma rampa de aquecimento controlada, enquanto tendo um *feedback* constante da posição e temperatura das amostras.

keywords

Densification, Sintering, Fast Firing, Ramp rate/Motion Feedback loop, Dynamic control.

abstract

The processes that occur during sintering of polycrystalline systems, are those of particle necking, densification, grain coarsening, porosity control, and segregation. These processes result from three mass transport mechanisms: surface condensation/evaporation, grain boundary diffusion, and lattice diffusion. The final microstructure can be varied by forcing a specific phenomenon to predominate over the others during the sintering process. For example, the fast-firing process represents a sintering procedure where the temperature–time (T–t) profile is altered to rapidly reach the T regime where densification dominates over grain growth. In this way, a small grain size can be maintained while still offering a high densification of polycrystalline materials. Therefore, the current work will design and build a mechanical device, to introduce ceramic samples into a furnace at a controlled ramp rate, with an instantaneous temperature/motion feedback loop.

List of Contents

List of Figures

List of Tabels

Nomenclature

PIC	Peripheral Interface Controller
IC	Integrated Circuit
LCD	Liquid Crystal Display
LED	Light Emitting Diode
GUI	Graphical User Interface
VB	Visual Basic
VBA	Visual Basic for Applications

1 INTRODUCTION

Nowadays given the continued evolution of materials based technologies, has driven the need for materials offering a specific set of pre-determined characteristics that are often closely linked with their microstructure. For this reason, the ability to control sintering mechanisms during the densification of ceramics has become an essential tool with which to tailor final properties such as electrical behavior, porosity and strength.

The objective of this work focuses on the design and construction of a mechanical device for use at a laboratorial level, which is capable of controlling the sintering of ceramic samples up to high ramp rates, while recording this data for subsequent analysis. Normally ramp rates greater than 50ºC/min are difficult to achieve with standard furnaces due to damage to the heating elements and insulation caused by the rapid heating. In contrast, the current design avoids this limitation by maintaining a constant furnace temperature and controlling effective temperature instead by the positioning of the sample in the hot zone.

The thesis is organized in five chapters, commencing with a bibliographic revision. In this first chapter particular focus is given to the sintering process. The theory of the sintering process is described, highlighting its controlling mechanisms .Various sintering methods are briefly explained and the salient method of this thesis, fast firing, is explained in more detail.

The second chapter outlines the theory of the technology selected in this project for the construction of the fast firing device.

The third chapter is dedicated to the description of the methodology and the design of the mechanical device and the selection of the materials and equipments acquired and assembled. This chapter also explains the operating principles for the control of the device.

In the fourth chapter, the experimental results and limitations of the device are explored as a function of different target temperatures and desired ramp rates

The overall conclusions are presented in the fifth chapter. This chapter discusses the outcome of the project and offers insight of potential future work to improve on the current performance.

1.1 OBJECTIVES

The developed work had as its main objective the elaboration of a device that can perform fast firing sintering experiments with a feedback loop offering continuous control of sample temperature. To be able to fulfill the task at hand, a number of different techniques and tools were used.

i) CAD Design of metal/ceramic joints, sample holder, sample support, motorized sample insertion, metal/ceramic joints.

ii) Control of thermal shock

iii) Precision control of motorized sample insertion.

iv) Electronic circuit design and microchip programming for computer interfacing.

v) The development of software for motion control and data acquisition.

vi) Analysis of experimental results

2 BIBLIOGRAPHIC FUNDAMENTS

2.1 SINTERING

By definition sintering can be described as the consolidation, densification, recrystallization and bonding between agglomerated powders during or following compaction, at temperatures below the melting point of the material (1) or as Herring defined sintering is "*…understood to mean any changes in shape which a small or a cluster of particles of uniform composition undergoes when held at high temperature*" (2).

There are four basic types of sintering processes; they are solid-state sintering (Figure 1), liquid-phase sintering, viscous sintering and vitrification. This paper is fully dedicated to the solid-state sintering process. During this sintering process occurs particle necking, densification, grain coarsening, porosity control and segregation.

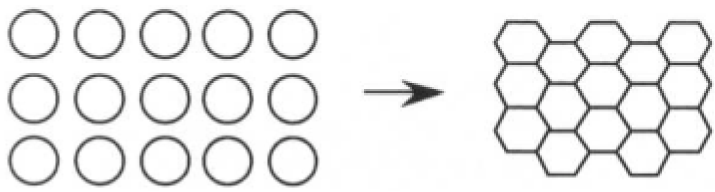


Figure 1- Solid-state sintering (1).

Over the years there were experimental studies and theoretical analyses that formed an exceptional qualitative understanding of sintering in terms of the driving forces, the mechanisms, and the influence of the principal processing variables such as particle size, temperature and applied pressure (3).

There are a number of parameters that can be easily identified on the sintering process, as the Table 1 lists.

Table 1- Important parameters in the sintering of ceramics (3).

Behavior	Models	Data Base
General morphology	Neck growth	Diffusion coefficients: anion and cation, lattice, grain boundary and surface
Pore evolution: size, shape, interpore distance	Surface area change	Surface and interfacial energies
Density: function of time and temperature	Shrinkage	Vapor pressure of components
Grain evolution: size and shape	Densification in the later stages	Gas solubilities and diffusivities
Grain size: function of time and temperature	Grain growth: porous and dense systems, solute drag, pore drag, pore breakaway	Solute diffusivities
Dopant effects on densification and grain growth	Concurrent densification and grain growth	Phase equilibria

Processing and Material Parameters	Characterization Measurements
Powder preparation: particle size, shape, and size distribution	Neck growth
Distribution of dopants or second phases	Shrinkage, density, and densification rate
Powder consolidation: density and pore size distribution	Surface area change
Firing: heating rate and temperature	Grain size, pore size, and interpore distance
Gaseous Atmosphere	Dopant distribution
Applied pressure	Strength, conductivity, and other microstructure-dependent properties

Some of the parameters can be controlled precisely such as the sintering temperature, the average particle size and the atmosphere while others such as the powder characteristics and particle packing are more difficult to control but still having a significant effect on the process.

2.1.1 SINTERING STAGES

The sintering process in solid-state sintering has three main stages. A sintering stage can be described as an "*interval of geometric change in which pore shape is totally defined (such as rounding of necks during the initial stage sintering) or an interval of time during which the pore remain constant in shape while decreasing in size*" (4). The sintering stages are named as initial, intermediate and final stage.

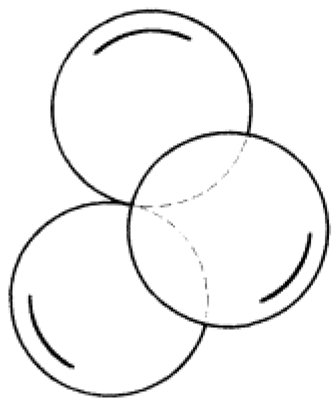


Figure 2- Ceramics model before sintering (5).

During the initial stage (Figure 3), the interparticle contact area increases by neck growth from 0 to almost 0.2. A reasonably rapid interparticle neck growth occurs in this stage either by diffusion, vapor transport, plastic flow or viscous flow. The relative density increases from 60 to 65 percent (6). The initial stage as indicated by Coble, involves no grain growth (7).

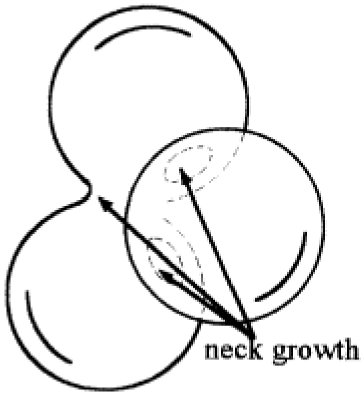


Figure 3- Model of the initial stage sintering (5).

The intermediate stage only begins after the pores have reached their equilibrium shapes as dictated by the surface and interfacial tensions. This stage is characterized by the continuous pore channels that are coincident with three-grain edges (Figure 4). The densification is assumed to occur by the pores simply shrinking to reduce their cross section and by having matter diffuse toward and vacancies away from the long cylindrical channels the relative density is increased by 65 to 90 percent (5) . By the time the pores become unstable and the separation starts isolated pores eventually begin to appear, this phenomena represents the ending of this stage (8). Most of the densification and microstructures changes take place in this intermediate stage.

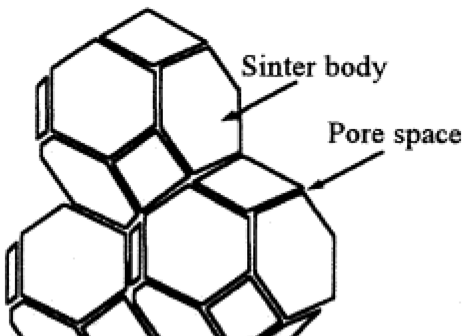


Figure 4- Model of the intermediate stage sintering (5).

When the pore phase eventually pinches off the final stage beings (Figure 5), it is characterized by the absence of a continuous pore channel. In this stage the pores are supposed to shrink continuously and acquire a lenticular shape if residing on the grain boundaries or rounded if residing within a grain. The mobility of grain boundaries and pores are increased, this factor must be controlled in order to achieve the required the theoretical density (5).

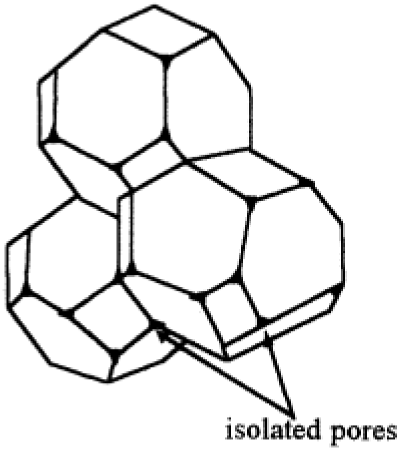


Figure 5- Model of the final stage sintering (5).

2.1.2 *Microstructure control*

Properties, such as the size and shape of the grains, the pore size and distribution in the body and the nature, and distribution of second phases are in the realm, of microstructure control and this greatly influences the engineering properties of ceramics. The sintering behavior and final grain size are affected in particular by the particle size of the starting ceramic material, the degree of accumulation and also by the microstructure of the green body, which in addition is also determined by the shaping technology used.

Usually while sintering occurs the coarsening of the microstructure due to the densification of the polycrystalline powder, the average size of the pores and grains gets greater. This phenomenon is very complex but simple approaches taken by engineers indicate that the achievement of high density and controlled grain size is dependent on reducing the grain growth rate or increasing the density rate (or a combination of both) (3).

To understand the sintering phenomena occurring while the sample material is at work we must first determine the type of densification taking place. There are various types such as solid-state, viscous, liquid-phase and vitrification sintering. The sintering process applied on the material at work produces densification of the solid-state type.

2.1.3 MECHANISMS OF DIFFUSION

Mechanisms of sintering are the phenomenon that allows the sintering of polycrystalline materials; this occurs by diffusion transport of matter along definite paths. There are six diverse mechanisms of sintering in polycrystalline materials, such as surface, lattice (the effect of lattice diffusion differs when it is located at the surface or on the grain boundary regions) and grain boundary diffusion, plastic flow and vapor transport, as can be seen in the Figure 6.

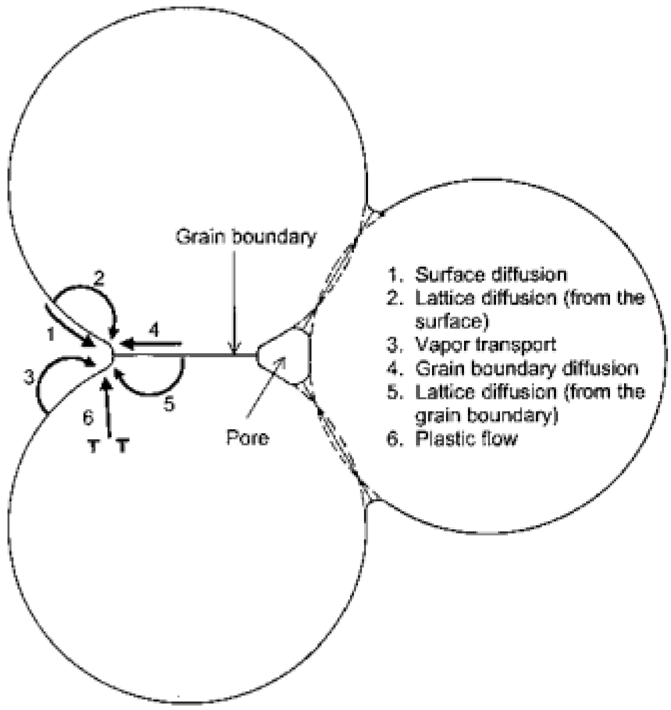


Figure 6- Distinct mechanisms of sintering on polycrystalline materials (3).

But only some lead to shrinkage or densification of the material. The distinction is usually made between *densifying* and *nondensifying* mechanisms. The *nondensifying* mechanisms are the diffusion mechanism, lattice diffusion from the particles surfaces to the neck and vapor transport. They belong to this group because while leading to neck growth they promote no densification of the materials. The *densifying* mechanisms are the grain boundary diffusion and lattice diffusion from the grain boundary to the pore; these are the most important sintering mechanisms while sintering polycrystalline ceramics. Lattice diffusion from the grain boundary to the pore also leads to neck growth. Plastic flow mechanism also leads to densification but the effect is much more common on sintering of metal powders.

During the sintering process there are transport mechanisms activated by increasing the temperature inducing then grain growth and densification on the material being sintered. The availability of several matter transport paths and the presence of grain boundaries increase the complexity of the sintering phenomena in polycrystalline materials over other types of sintering methods.

Diffusion in the boundaries of polycrystalline bodies is recognized as influencing many physical and metallurgical processes such as grain growth, re-crystallization, plastic deformation and whisker growth (8)

The major solid-state mechanisms of matter transport in sintering of polycrystalline material are lattice diffusion (also referred to as volume or bulk diffusion), grain boundary diffusion and surface diffusion (condensation/evaporation) (9).

Each mechanism of diffusion has a different impact while the sintering of polycrystalline ceramics takes place. While coarsening and grain growth are primarily related to surface and grain boundary diffusion, the impact of lattice diffusion is mainly on densification and porosity elimination, where the grain boundary diffusion type has lower influence. By understanding the mechanism of diffusion, it is possible to influence which mechanism has the dominant effect and in this way to control the final microstructure.

The diffusion coefficient $D_i(T)$ is defined according to the next expression:

$$D_i = D_0 \times e^{\frac{-Q_i}{R.T}} \qquad (2.1)$$

Where D_0 is a constant, Q_i is the activation energy of the diffusion process; R is the gas constant and T the absolute temperature. The fact that the diffusion phenomena are thermally activated in solid materials creates the possibility to control the resultant microstructure by manipulation of the characteristic temperature dependences of each process. For polycrystalline materials the characteristic activation energies of each process are given as followed:

$$Q_s < Q_{gb} < Q_l \qquad (2.2)$$

Being Qs the surface diffusion activation energy, Qgb the grain boundary activation energy and the Ql the lattice diffusion activation energy (10).

2.1.3.1 Lattice diffusion

Lattice diffusion refers to atomic diffusion within a crystalline lattice (4). The mechanism of lattice diffusion changes according to the type of defect encountered. It can be either vacancy or interstitial defects being the mechanism designed as vacancy mechanism or interstitial mechanism correspondently. This phenomenon involves grain bulk and involves a higher activation energy than the surface mechanisms. Although there are four types of lattice diffusion there are two mechanisms that have the most influence and therefore gain more importance. These are the vacancy and interstitial mechanism, the others are the interstitialcy and the ring mechanisms (3). These mechanisms will be described briefly below.

2.1.3.1.1 Vacancy mechanism

Atoms on a normal lattice site exchange places with a vacant site. The vacancy concentration is affected by the temperature, solute and atmosphere. The diffusion coefficients of the atoms and the vacancies are related but not equal. An atom can only jump if a vacancy is located on an adjacent lattice site, but a vacancy can jump to any of the occupied nearest neighbor sites. The number of atomic jumps will be then proportional to the fraction of sites occupied by vacancies (Cv). The relation between the coefficients atomic diffusion and vacancy diffusion can be explained by the follow expression:

$$D_a = C_v \times D_v \qquad (2.3)$$

Being D_a, Atomic diffusion coefficient, D_v, vacancy diffusion coefficient and C_v, fraction of sites occupied by vacancies.

The Figure 7 represents the vacancy mechanism phenomenon.

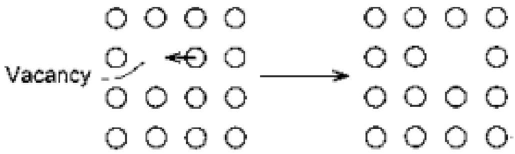


Figure 7- Lattice diffusion by vacancy mechanism (3).

2.1.3.1.2 Interstitial mechanism

The interstitial defect phenomenon takes place when atoms which occupy a site in the crystal structure at which there is usually not an atom, or two or more lattice sites such that the number of atoms is larger than the number of lattice sites. This happens when the solute or regular atoms are small enough to be located in the interstitial sites of the lattice (Figure 8).

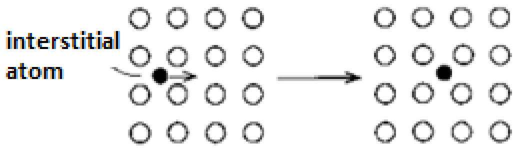


Figure 8- Lattice diffusion by interstitial mechanism (3).

A relationship analogous to the equation that represents the vacancy phenomenon can still be used:

$$D_a = C_i \times D_{ic} \qquad (2.4)$$

Being D_{ic}, interstitial diffusion coefficient and C_i , concentration of the interstitial atoms.

2.1.3.1.3 Interstitialcy mechanism

If the distortion of the lattice becomes too large for interstitial diffusion to be favorable, then movement of the interstitial atoms may occur by the interstitialcy mechanism. An atom on the regular lattice site exchanges position with a neighboring interstitial atom (they do not need to be the same type of atoms) (Figure 9).

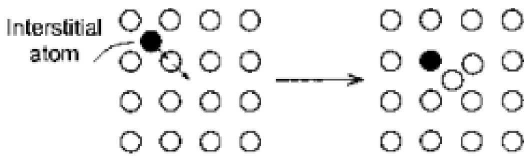


Figure 9- Lattice diffusion by interstitialcy mechanism (3).

2.1.3.1.4 Ring mechanism

In ring mechanism an atom exchange takes place by rotation in a circle without the participation of a defect. Several atoms can participate in a simultaneous exchange. The significant momentary distortion couple with the large energy changes arising from electrostatic repulsion makes this mechanism improbable in ionic solids (Figure 10).

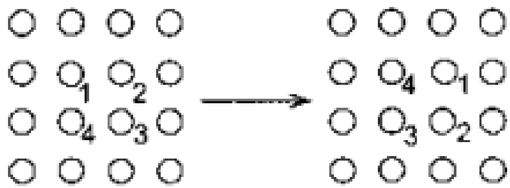


Figure 10- Lattice diffusion by ring mechanism (3).

Other mechanisms of diffusion as referred before are the grain boundary diffusion and the surface diffusion

2.1.3.2 GRAIN BOUNDARY DIFFUSION

Grain boundary diffusion plays a key role (by often controlling the evolution of structure and properties of the materials)in many processes occurring in polycrystalline bodies at elevated temperatures, such as Coble creep, sintering, diffusion-induced GB migration (DIGM), different discontinuous reactions, recrystallization and grain growth (11). Grain boundaries in polycrystalline materials are the designation of the separation between crystal (also known as grains) from each other by regions of lattice mismatch and disorder. Grain boundary diffusion can be swifter than the lattice diffusion in the adjacent grains because of the highly defective nature of the grain boundary. The grain boundary diffusion is affected by the grain size present in the material, so to obtain a constant grain boundary width the fraction of the solid that is occupied by the grain boundary increases with the decreasing grain size (3). Grain boundary diffusion is sensitive to the grain boundary structure and chemical composition and it the diffusion can be studied with modern radiotracer methods without disturbing the grain boundary state (11).

Most mathematical treatments of Grain boundary diffusion are based on Fisher´s model (12)

2.1.3.3 SURFACE DIFFUSION

This type of diffusion plays an important part in crystal and film growth, in evaporation and condensation, in surface chemical reaction and catalysis, in sintering as well as in other surface processes.

3 CONTROLLING THE FIRING (SCHEDULE)

Fast Firing, also known as rapid sintering, is a sintering process where the heating cycle control subjects the sample material to a short firing at high temperatures. For some materials, this process will provide equivalent densities at smaller grain sizes in a less energy consuming process.

To have benefits from the use of this process several parameters need to be known before starting the sintering such as: The controlling mechanism for the process of densification and coarsening and reliable data for the activation energies for the appropriate diffusion coefficients.

The best situation to utilize the fast firing technique is when the activation energy for densification is greater than the energy for coarsening, meaning that at higher temperatures the densification rate would be faster than the coarsening rate (3), Figure 11.

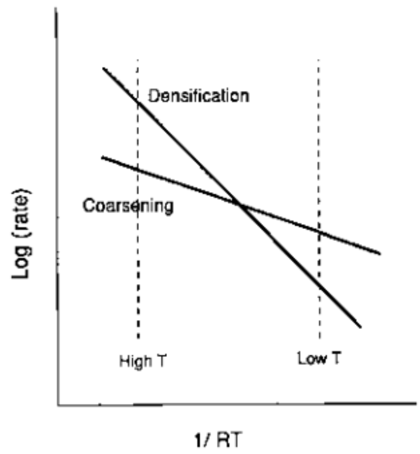


Figure 11- Effect of a fast heating rate on a ceramic material (3).

The process usually involves a rapid insertion of a specimen into a preheated furnace at high temperatures followed by soaking at maximum temperature for shorter times than used in conventional sintering (4).

Densification with lower grain growth is achieved due to the rapid passage of the sample thorough the low temperature regime where grain coarsening dominates, into the region where the densification mechanisms prevail. A fast heat-up can provide an effective route for the formation of a dense material, while avoiding grain growth, where $\dot{\rho} > \dot{G}$.

The occurrence of heat conduction happens during the process because energy is absorbed in the surface of the material which is then transferred into the bulk of the sample.

Figure 12 shows an example of fast firing, selected from the literature. A series of experiments to test the different fabrication process of Al_2O_3 doped with 200 parts-per-million (ppm) MgO were performed. This figure illustrates clearly that choosing the right process is crucial for the microstructure control and the fast firing technique can provide dense samples with reduced grain size.

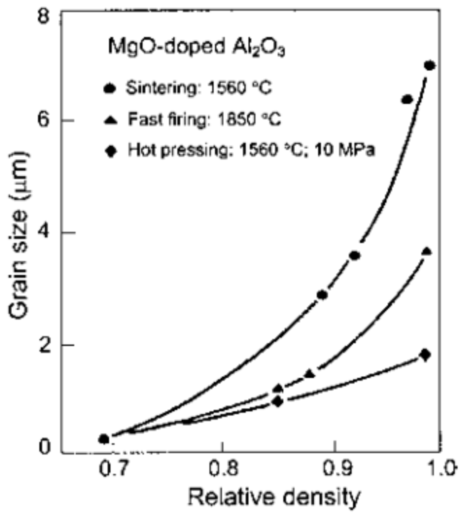


Figure 12- Experimental results for microstructural development / grain size versus density trajectories for fabrication by hot pressing, conventional sintering and fast firing (7)

As stated by Bradeau (5) the temperature gradient is very significant in mass transportation, further analysis in this subject by Searcy suggests that temperature in driving densification during fast firing (9). Improved diffusion is then a result of fast sintering the sample as undertook

3.1 SUPPORT TECHNOLOGIES

To successfully control the system a real time analysis of parameters assumes a vital importance. The constant monitoring of the different parameters, such as temperature, position and the human input controls must be made instantaneously without flaws in the receiving or sending of the data packages. Such feedback is essential for optimum control of the system and for it to be autonomous use.

To implement the monitoring and control several technologies were considered for the development of the system. In the current section different existing protocols will be addressed to enable the communication between devices with enough functionality to control the system. The used protocols and equipments are in agreement with the model Open Systems Interconnection (OSI) (13).

The OSI model was created by the International Standards Organization (ISO) as an answer to the increasing number of architectures of proprietary and specific communications protocols by a particular manufacturer. This model serves as a reference by which others can be created. The OSI model was originally developed to be a detailed specification of an abstract interface. It is no more than a description or model of reference of how the information must be transmitted between two equipments on a network, regardless of any hardware being used (14). This model is organized in seven layers, the order of the diverse layers can be understood by reference to the Figure 13.

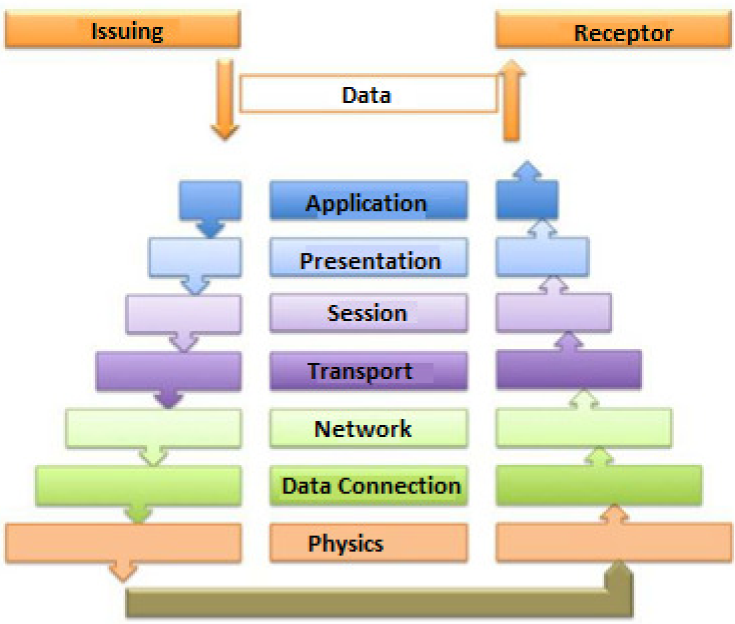


Figure 13- Layers of OSI model (Edited from (14)).

The **application layer** is responsible for the support to the user applications. This goes for either the receiving side or the receptor. Services of files transfer (FTP), email are some of the examples of services available in the libraries of this layer.

The **presentation layer** is responsible for the delivery and formatting the information to the application layer for further processing or display. It relieves the application layer of concern regarding syntactical differences in data representation within the end-user systems. This layer deals with issues of string representation. There are applications and protocols where no distinction is made between the application and presentation layer for example, the HTTP protocol (HyperText Transfer Protocol) generally regarded as an application layer protocol, has Presentation Layer aspects such as the ability to identify character encoding for proper conversion, which is then done in the application layer.

The **session layer** is the fifth layer of the OSI model of computer networking. This layer provides the mechanism for opening, closing and managing a session between end-user application processes. The communication sessions consist of a request and responses that occur between applications. These services are normally used in application environments that make use of remote procedure calls (RPCs). The Session layer responds to service request from the Presentation layer and issues service request to the transport layer. The Session Layer of the OSI model is responsible for session checkpointing and recovery. It allows information of different streams, perhaps originating from different sources, to be properly combined or synchronized.

3.1.1 PHYSICAL LAYER PROTOCOLS

The serial standard Rs-232 was developed in 1962 by EIA (“Electronic Industries Association), with the goal to enable the communication between a computer and a modem; nowadays it is available to a bigger range of other connections (15). This standard suffered some revisions since it was created, being the last the Rs-232-F made in 1997. As with any other serial transmission equipment, the bits are sent one by one sequentially and usually with the left bit being the less significant (LSB). For being an asynchronous protocol (without a clock line) it is the emitter and receiver responsibility to coordinate the respective time cycles to start and end each bit. The signals on a Rs-232 communication are transmitted with voltage of ±5V.

In its standard form the Rs-232 protocol uses two different control signals, the RTS (Ready to Send) and the CTS (Clear to Send) to manage the flux of data exchange by hardware (Whenever the emitter starts sending data the RTS pin is flagged. The RTS pin being flagged makes the receiver understand that there is data arriving the CTS pin goes to the level high (as “1”) confirming the sending (“Acknowledge”). Only after receiving the signal from the CTS pin can the emitter start the transmission. The RS-232 standard defines the electrical, mechanical and functional characteristics allowed. The transmission rate and maximum extend of the line are not defined, but they are normally 115200 bit/s and the capacitance should not exceed 2500 pF, respectively (15).

This standard does not define the settings to be used by the data connection. Normally seven or eight bits of data are used and one start bit to initiate of the string and one or two to end the same. Other bits may be included to control the errors (Parity bit) and the flux control by hardware or software.

The connection made by equipments is usually done through wires with connector (DB-25 or DB-9, being the last one the most used nowadays). In the Figure 14 can be seen both types of connectors referred in a connection between two equipments.

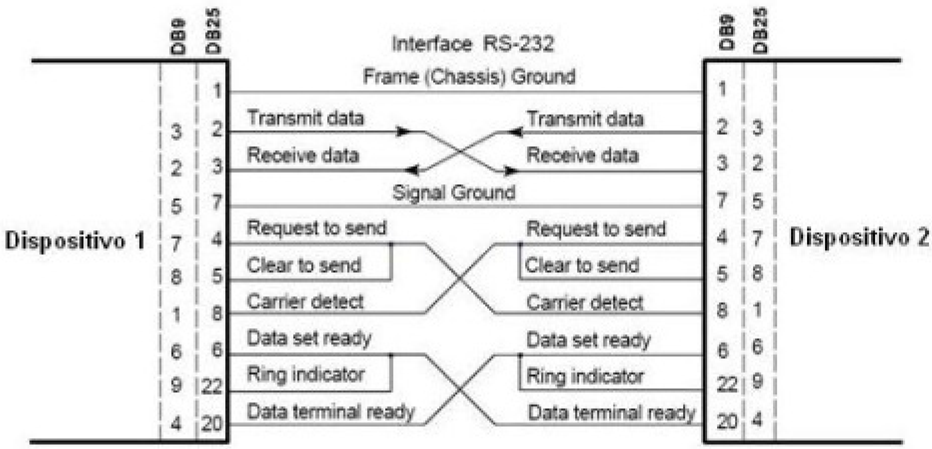


Figure 14- Rs-232 communication between a computer and a terminal (15).

Currently the Rs-232 standard communication is being gradually substituted by the USB standard for the local connection, because the USB is faster, has easier to use connectors and possesses a better software support. But the Rs-232 is still being used in many vending points (bar code registers, or magnetic tape, amongst others) and in industrial machinery (remotely controlled devices). For this reason some computers have inbuilt Rs-232 doors (onboard, or in boards with PCI or ISA bus enabled) , although even if most modern computers don´t have this function available there are USB to Rs-232 converters that fix this aspect.

The Serial Peripheral Interface (SPI) is used primarily for a synchronous serial communication of host processor and peripherals.

The SPI can be used with a wide variety of peripheral equipments and they can be subdivided into the following categories (16):

- Converters (ADC and DAC)
- Memories (EEPROM and FLASH)
- Real Time Clocks (RTC)
- Sensors (temperature, pressure)
- Others (signalmixer, potentiometer, LCD controller, UART, CAN controller, USB controller, amplifier)

The standard configuration for a slave device is described in Figure 15.

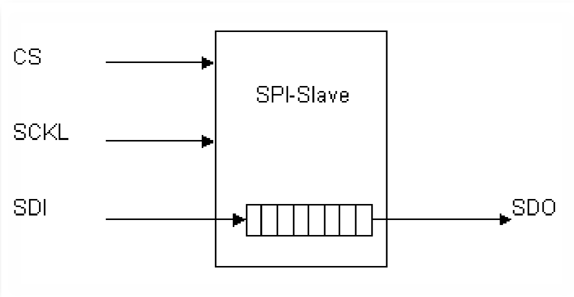


Figure 15- Standard configuration for a slave device (17).

With this configuration two control and two data lines are used. To enable this standard there must be a master device and a slave device. The master provides a clock signal and determines the state of the chip select lines (this function determines which slave the master is communicating with). Using the master/slave relationship, the master starts the communication by generating a clock and selecting the device, the data can be transferred on both directions simultaneously (by definition data is always sent both directions but it is up to the devices to know whether a received byte is meaningful or not). Within the data transferred there is at the start a dummy byte to start the read/send functions.

The SPI requires two control lines (CS and SCLK) and two data lines (SDI and SDO, these can also be known as MOSI (Master-Out-Slave-In) and MISO (Master-In-Slave-Out), as they were labeled by Motorola), to select the slave devices the line is named SS (Slave-Select).

With CS (Chip-Select) the corresponding peripheral device is selected. This pin is mostly active-low. In the unselected state the SDO lines are hi-Z and therefore inactive. The master decides with which peripheral device it wants to communicate. The clock line SCLK is brought to the device whether it is selected or not. The clock serves as synchronization of the data communication(18).

The majority of SPI devices provide these four lines. Sometimes it happens that SDI and SDO are multiplexed, for example in the temperature sensor LM74, or that one of these lines is missing. A peripheral device that must or cannot be configured requires no input line, only a data output for example the integrated circuits Max6675 or Max31885. As soon as it becomes selected it starts sending data. In some ADCs, therefore, the SDI line is missing. There are also devices that have no data output. For example, LCD controllers that can be configured, but cannot send data or status messages.

Figure 16 describes the control over a number of slave devices by splitting the CS pins into a number equal to the slave devices needed, the slave enabled and consequently the one that is sending/receiving data is determined by the state of the CS pin (High or Low states) that is changed the program sent to the microchip.

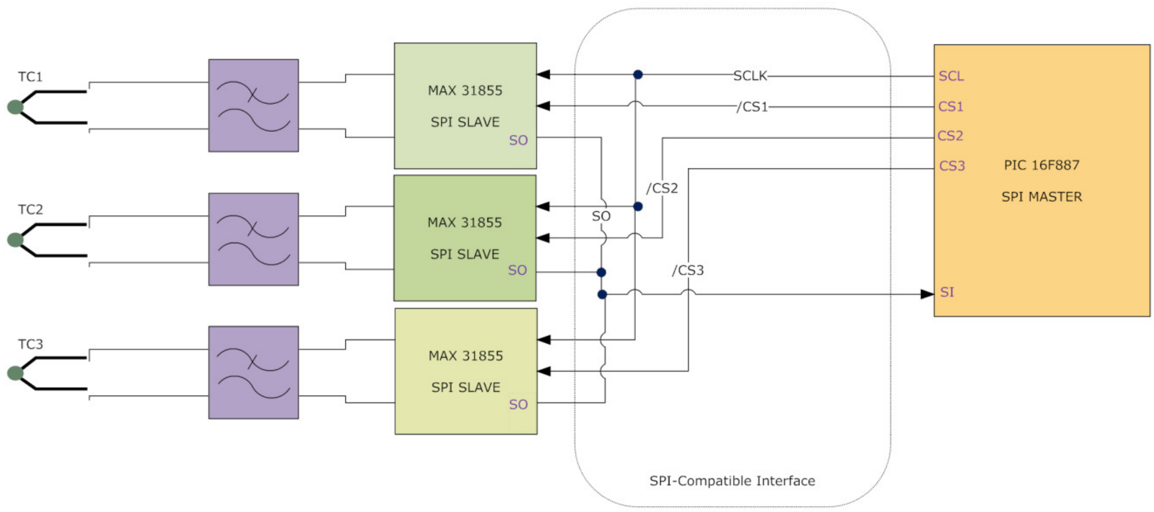


Figure 16 - Serial Peripheral Interface (16).

3.2 CONTROL SYSTEM

The main objective of this thesis is to create a dynamic system that enables the user to perform a fast firing operation with the samples. A dynamic system is usually a combination of two or more systems, currently there are electrical, fluid, mechanical and thermal systems. The ones used in this work are the mechanical and electrical (19).

While elaborating a project there are various considerations to be taken such as:

- Low budget
- Effects of the furnace on the materials
- Time of work effects
- Motor speed / Resistance
- Dimensions of the system fully built "rather" small

These conditions affected the project result especially the low budget and the maximum dimensions of the system built. From the start to the end of the project every major decision will be explained in detail in this work on the following chapters.

3.2.1 TYPE OF SYSTEM

There are different types of control systems that can be applied on this work, but the chosen method was the On-Off with feedback control. In the Figure 17 a basic linear feedback controller is presented.

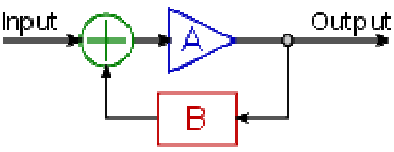


Figure 17- Basic feedback loop.

The feedback control exists when two or more variables can affect each other

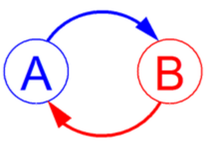


Figure 18- Open-loop.

An On-Off control with feedback drives the manipulated variable from one state to another depending on the position of the controlled variable relative to the setpoint. A common example of on-off control is the temperature control in a domestic heating system. When the temperature is below the thermostat setpoint the heating system is switched on and when the temperature is above the setpoint the heating switches off, this example can be represented with block diagram in the Figure 19.

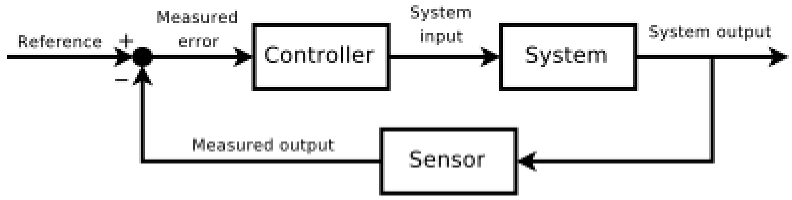


Figure 19- On-Off Control System.

3.2.2 MICROCONTROLLER AND MICROPROCESSOR

A microprocessor is a general purpose digital computer central processing unit. Although it is widely known as a "computer on a chip" the microprocessor is in no sense a complete digital computer. After the engineering community became aware of the 8bit processors in the middle to late 1970's the microprocessors started to gain usefulness in a very broad number of tasks such as data gathering, machine control, human interaction and other applications that granted a limited intelligence to the machines. The bit size, cost per unit and power demanded to work are some of the most favorable points over other types of hardware.

A by-product of the microprocessor was the microcontroller. These devices possess the same fabrication techniques and programming concepts, although, they became different in some of the "architecture" designs implemented because of the final use the device will have.

By comparing the attributes of each device we can extrapolate that the microprocessor is concerned with rapid movement of code and data from external addresses to the chip and it will require additional parts to be operational. The microcontroller on the other hand can function as a computer with the addition of no external parts and it is mainly focused in rapid movement of bits within the chip (20).

The different on the "architecture" design can be seen on the Figure 19 and Figure 20.

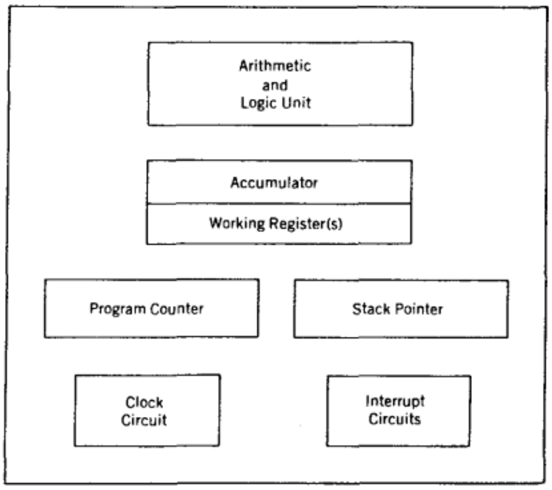


Figure 19- Design architecture of the microprocessor (20).

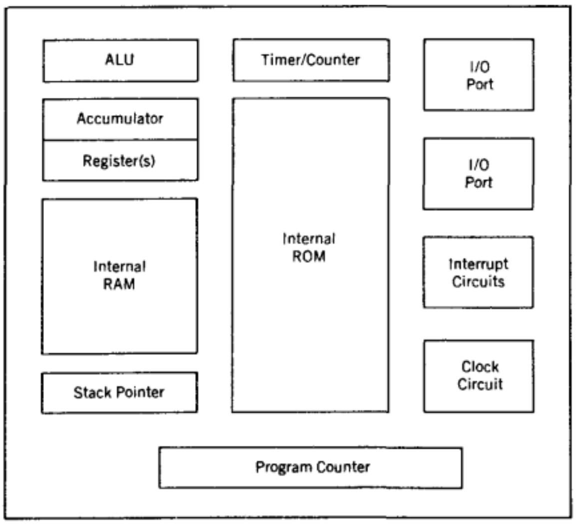


Figure 20- Architecture design of the microcontroller (20).

The work required on this thesis requires a microcontroller instead of a microprocessor. This will enable the construction of a program that will control with effectiveness the sample holder position.

3.2.3 DESIGN OF A MICROCONTROLLER

The design of the microcontroller incorporates all of the features found in a microprocessor (ALU,PC ,SP and the registers), also adding other features required to perform all the operations a computer can do such as ROM(read-only memory),RAM (random access memory), parallel I/O, serial I/O, counters and a clock circuit.

The main use of the microcontroller is to control the operation of a machine using a fixed program that is stored in ROM and that does not change over the lifetime of the system (20). The design it took makes it usable on many applications, it accomplishes this feat by having a very flexible and extensive repertoire of multi-byte instructions (21), the hardware configuration.

There are tools and resources needed to work with microcontrollers in this work we used a microchip microcontroller (Picmicro) such as:

- An assembler or a high-level language compiler (C language with Hi-Tech C compiler).
- A computer to run the software and develop it.
- A hardware device (Programmer) that connects through the serial, parallel or USB line.
- Cables to connect the programmer to the computer and to connect the Pic to the programmer.
- Pic microcontroller.

Prototypes circuits are usually made in breadboards and we followed this “trend” by building a fully operational controller in the breadboard.

There are at least a dozen manufactures of microchips in the world and each has its own assembly language to program the devices, so as a result, a decade ago every time a user changed the type of the device it would have to recode/learn a new programming language before starting to elaborate a project. Nowadays, there are high-level language compilers that can translate the code into numeric values for the PICmicro (Hexadecimal). These compilers offer many advantages to the programmer such as the multi-platforming, program maintenance, the posterior testing and the lower probability of having errors within the code. Nonetheless, it also has some short comings such as the memory it takes on the microcontroller, the length of code becomes greater and it runs usually slower.

3.2.4 INTERFACE APPLICATION

The interface application is at core a program that enables the user to control and view the results that the system is performing with each command without having to understand how the system works or the underlying logic of the stored program. It is intended to be simple, intuitive, efficient and responsive to let the user to start working and finish the task at hand without much effort or time needed to learn it.

This is, as a rule, called as graphical user interface (GUI). The term came into existence because the first interactive user interfaces to computers were not graphical; they were text-and-keyboard oriented and usually consisted of commands you had to remember and computer responses that were infamously brief. The command interface of the DOS operating system (which you can still get to from your Windows operating system) is an example of the typical user-computer interface before GUIs arrived. An intermediate step in user interfaces between

To create the interface application the software Microsof Visual Basic 2010 Express was used. Visual Basic 2010 Express is Microsoft´s latest version of Visual Basic.NET programming language. This software greatest strength is its ease of use and the speed it enables the programmer to create Windows Forms, WPF Windows, Web and mobile devices applications among others (22).

It is an object-oriented computer programming language and it is currently supplied on two major implementations.

4 PROJECT

As mentioned in the state of art, to sinter samples using the method of fast-firing it is required to achieve high temperatures under a certain fraction of time. This work aims to project and build a system that successfully accomplishes this goal. The fast firing project had some pre-requisites has minimum temperature on the furnace of 1250 °C and the furnace also had to be open on both sides, the linear guide to possess a speed of 200 mm/s and the real time answer of the circuit. The project was planned in function of the process to be used, the size of the equipment and the assembly of the different would need to be clear and simple. A limited budget was also taken in account.

4.1 FAST FIRING PROCESS

The fast firing process can be applied at least by two different ways: i) fast firing process with adjustable temperature and constant position, or ii) variable position with constant gradient of temperature in the furnace.

4.1.1 ADJUSTABLE TEMPERATURE

During the sintering process the samples used in the experiment are maintained in the same place while the temperature is controlled by a computer or a PLC.

One of the advantages of this method is the space occupied by the machine. The need for a Belt or a linear guide is non-existent since the ceramic samples are stationary.

A representation of this method is explained on the following Figure 21.

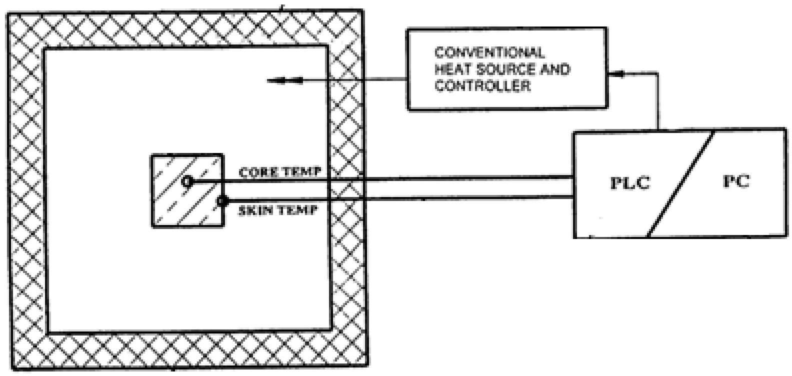


Figure 21- Method for controlling the firing of ceramics (United States Patent 6511628).

4.1.2 CONSTANT GRADIENT OF TEMPERATURE

The constant gradient of temperature consists on having a controlled belt or linear guide to move the materials in the furnace at a given ratio. The temperature inside the furnace has a known gradient along its course. The movement/speed of the materials is calculated using the uniform temperature distribution.

This method allows the sintering of materials in a continuous way by allowing various materials to be processed at the same time; this fact makes this method very useful and a reason why it is so widely used in the industry. One example of these fast firing furnaces can be found on the Figure 22.

Figure 22- HSK series fast fire furnace (Ieco).

4.2 Fast Firing Project

The chosen method used on this work was the constant gradient of temperature, based on the method explained on the subchapter 4.1.2. This version does not reach the high costs of the example mentioned, while performing and executing the experiment with an acceptable precision of the results. The furnace although does not have a controlled atmosphere (because it is open on both sides) and the linear guide does not allow multiple samples to be sintered at the same time. The project consists on controlling the Temperature/Time ramp. To this it was developed a project which used a Thermocouple, a linear guide, a step motor, a furnace and various support components.

4.3 Control system

The control system designed and built for this particular work can be visualized in the scheme (Figure 23). The flow of information (data packages) between the devices can be understood by interpretation of the scheme.

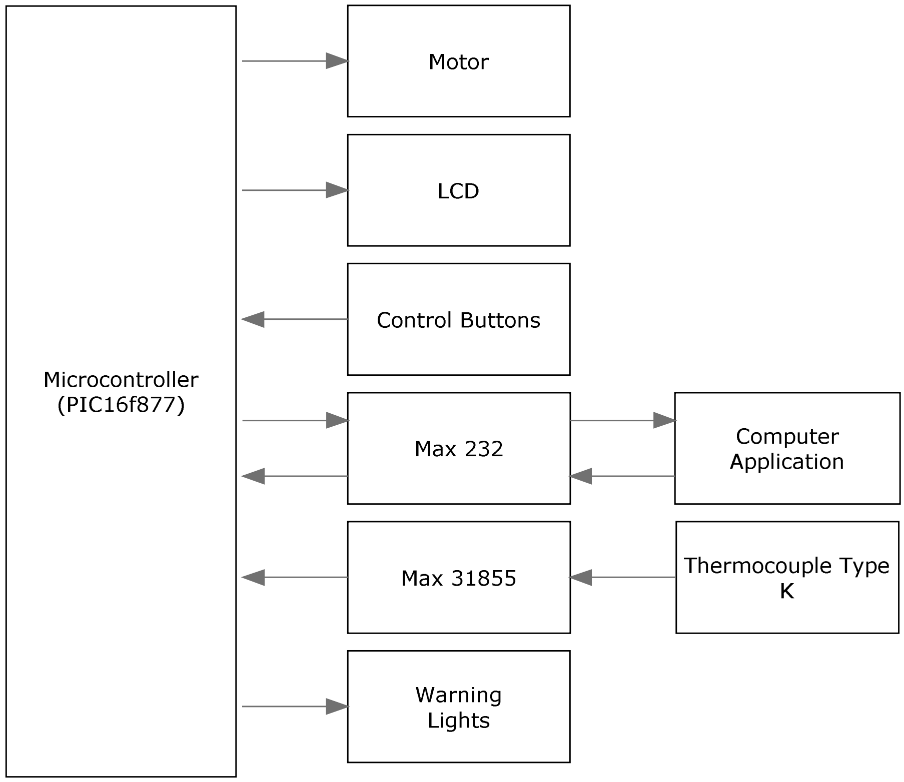


Figure 23- Control system scheme.

The system was designed with the objective of being both easy to understand by the usual user and the possible engineer who might want to upgrade or change any aspect or parameter of this system.

The flow of the information is described by the scheme presented in Figure 23.

The measurements of the temperature at the position of the samples, is done by the thermocouple. These data are then translated into an analog signal in the microcontroller. After this the temperature is sent to an application installed in the computer over a RS-232 communication as a data string (this string also includes the position of the sample holder). If using the automated movement of the motor the user is then prompted to choose a sintering rate, then with an algorithm created with the objective of controlling the speed of the motor receives the temperature and position of the samples and decides what is the proper speed to produce the effect of sintering on the samples material, or the direction of the movement depending on which mode of operation the user is working After calculating the adequate speed, the information is transmitted to the microcontroller (again over the RS-232 communication).

After this step, the motor will start moving at the speed wanted and on the liquid crystal display (LCD) both the sintering rate and the current position of the samples are shown.

4.4 MICROCONTROLLER

The electrical circuit was developed with the objective to control the movement of the “CAR” that supports the alumina bar carrying the samples to be sintered. This movement is controlled rigorously with a status check of the data (Temperature of the samples and the position of the CAR).

When building industrial or commercial machinery we can apply a multitude of procedures. We could choose to use microcontrollers (as was opted in this case), programmable logic controllers (also known as “PLC”) or the use of interconnected relays designed using ladder logic. These are logic controlled systems that may respond to switches or light, pressure sensors between others. With the response we can have the machine do a number of tasks such as start or stop.

The microcontroller was chosen for the present device by the fact that it is lighter, smaller, but mostly because it is a much cheaper device than a programmable logic controller (PLC). Although there are some benefits in having a PLC, such as robustness (it can endure sand and hits, which makes it more suitable for industrial applications) and the ladder logic used is much easier to understand and rewrite, there are not enough reasons to justify the cost of this option in the current work.

The microcontroller selected was the PIC 16F877 (Figure 24).

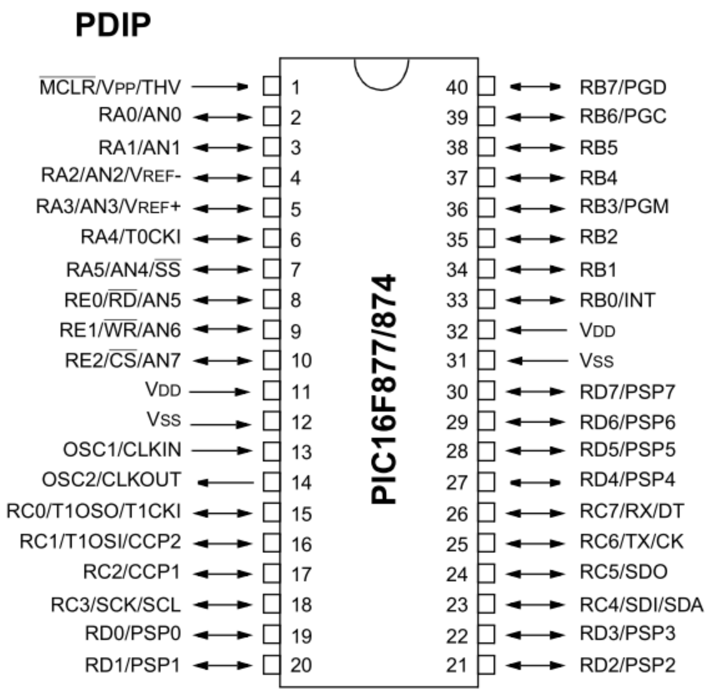
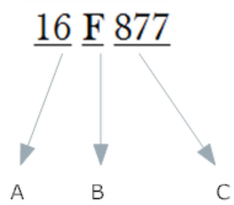


Figure 24- PIC 16F877 as in the datasheet (datasheet).

Some of the characteristics it possess can be directly extracted from its name



Being,

A: Number “16” which symbolizes the MID-Range devices from microchip. It belongs to the 8 bit family, meaning that the ALU (Arithmetic and Logique Unit) is read with words with the length having the maximum of 8.

B: Letter “F” is followed by the meaning that the PIC is of the Flash type. Each line of memory is a 14 word bits.

C: Numbers “877” allows us to know exactly the PIC we have chosen between all the other series of devices.

Flash memory is non volatile, so it can be used to store the user program and for posterior use it can be erased or reprogrammed electrically. Although there are other devices with more than 8k program memory it was decided that for the control system at hand it would not be need any more memory. In the future if any data should be stored it can always be built within the circuit an EEPROM memory for data storage and for the use of the microcontroller during the process.

The organization of the pins is described in the Figure 25; with this information the building/programming of the project can be started.

For this work the crystal oscillator type used was the 4Mhz, it is an electronic oscillator that uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency. This provides a stable clock signal for digital integrated circuits. The oscillator belongs in the pins numbered as 13 and 14 (OSC1 / OSC2)

The Pin 1 is designed as MCLR/Vpp/THV is the mode on which the microcontroller boots in, either in programmer mode (to insert the program the developer created), master clear entry (Reset), or high voltage test control. It is decided the way it boots with voltage supplied to this pin, for example to start running the program is 5V and to enable programming mode it is 4V.

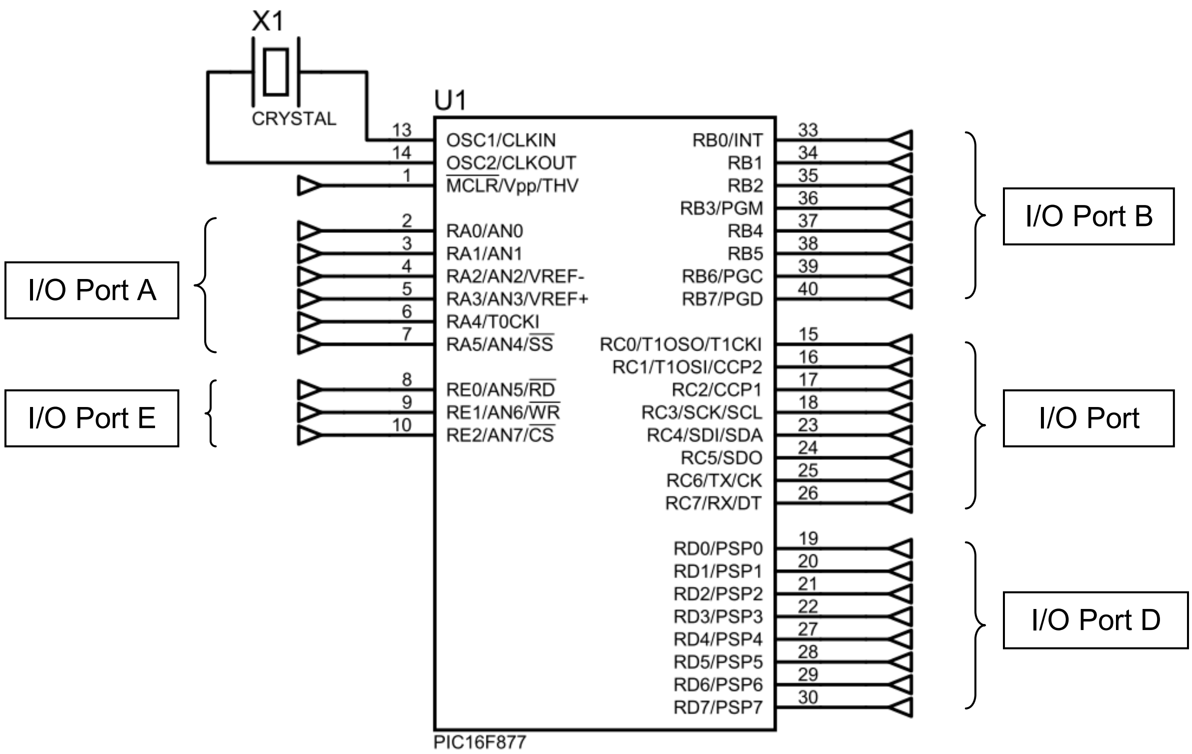


Figure 25- Simplified representation of Pic 16F877.

In order to reduce the confusion and to offer a better understanding it will be used in the circuit diagrams the simplified representation of the microcontroller Pic 16F877.In this the I/O Ports are organized in order of groups and numbers inside the groups, and the voltage supplier and the ground pins are not represented.

Some of the I/O Ports are multiplexed with alternative functions to access features from peripheral devices, being this the main reason to have five main groups in this device (Port A, B, C, D, E). For example most I/O pins on Port A can be used as either a general I/O pin or as an analog input (this function is being used to receive the measurements of the thermocouple), on Port C the I/O pins RC6 and RC7 are used as the transmitter and receiver respectively of the data packages over the RS-232 communication.

For the project the general purpose of each I/O ports are as followed:

Port A – Status LEDs (*Light Emitting Diode*)

Port B – Stepper motor involved circuitry

Port C – RS-232 communication and Temperature measurement

Port D – LCD involved circuitry

Port E – Control buttons and interrupts

4.5 BIPOLAR STEPPER MOTOR

After careful considerations, the type of motor chosen was the stepper motor.

The stepper motor is an electromechanical device that converts electrical pulses into discrete mechanical movements. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motor rotation has several direct relationships to this applied pulse. The sequence of the input pulses influences directly the direction of the movement as well as the speed by the frequency the input pulses occur, while the number of input pulses is related to the length of the motor rotation.

The stepper motor is used on a very wide number of applications thanks to its precision, reliability, precise positioning and the repetition of the same movement. The accuracy of a step motor is of 3 – 5% per step and this is error is not cumulative from one to step to the next, but it has as a disadvantage due to the difficulty of controlling the operation at high speeds.

There are three basic stepper motor types:

- Variable-reluctance ("VR")
- Permanent-magnet ("PM")
- Hybrid

The stepper motor used in this work is a hybrid one. As the name indicates this motor is a combination between the two other types and it groups the best features of the permanent-magnet and the variable reluctance motor types. The hybrid stepper motor although being more expensive than a permanent-magnet type, provides better performance concerning step resolution, torque and speed. The range of the step angles usually vary between 3.6° to 0.9° (100-400 steps per revolution). The rotor is multi-toothed like the VR motor and contains an axially magnetized concentric magnet around its shaft. The teeth on the rotor provide an even better path that helps guide the magnetic flux to preferred locations in the air gap. This further increases the detent, holding and dynamic torque (15).

The step motors are mostly two-phase motors (the motor chosen is also a two phase motor). These can be **unipolar** (Figure 26) or **bipolar** (Figure 27).

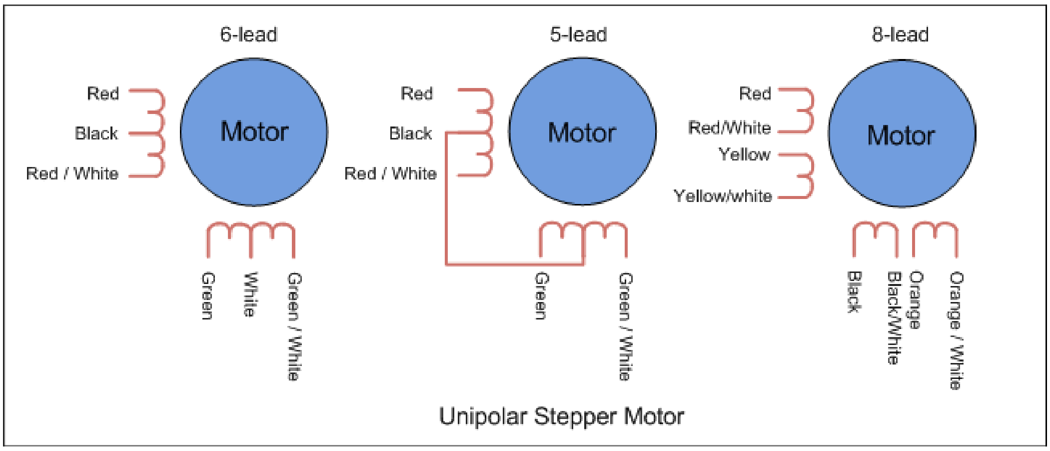


Figure 26- Unipolar stepper motors.

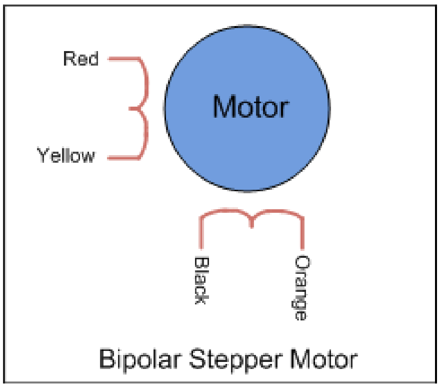


Figure 27- Bipolar stepper motor.

In unipolar step motor there are two winding per phase. The two winding to a pole may have one lead common i.e. centre tapped. The unipolar motor so, have five, six or eight leads. In the designs where the common of two poles are separate but centre tapped, motor have six leads. If the centre taps of the two poles are internally short, the motor has five leads. Eight lead unipolar facilitates both series and parallel connection whereas five lead and six lead motors have series connection of stator coils. The unipolar motor simplifies the operation because in operating them there is no need to reverse the current in the driving circuit. These are also called bifilar motors. In bipolar stepper there is single winding per pole.These are also called unfiled motors.

Although it is easier to control the operation of a unipolar stepper motor, the bipolar motor produces the maximum speed and torque available for the circuit at hand, this fact occurs due to the physical space occupied by the windings. A unipolar motor has twice the amount of wire in the same space, but only half is used at any point in time, therefore it is only 50% efficient (or in the region of 70% of the torque output available).

To move the stepper motor there are three methods. The stepping method refers to pattern of sequence in which the stator coils are energized, they are:

I. Wave drive

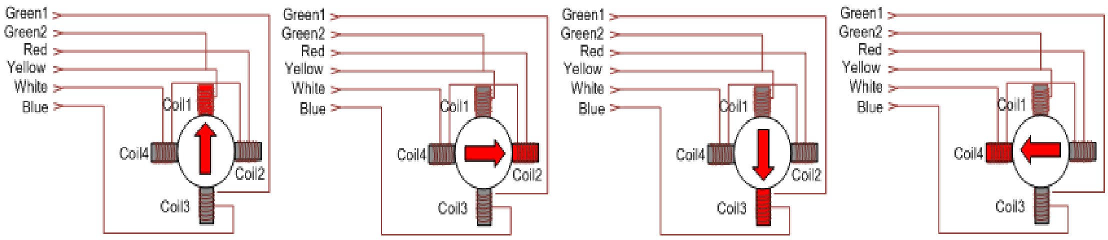


Figure 28- Representation of the Wave drive effect on the stepper motor coils(23).

In this drive method only a single phase is activated (or energized) at a time. Although it shares the same number of steps as the full step drive the motor will be less powerful than it would be by using full drive. This phenomenon occurs because only one winding is energized. This is the least used stepping method because of the mentioned disadvantage comparing with the other methods.

II. Full drive

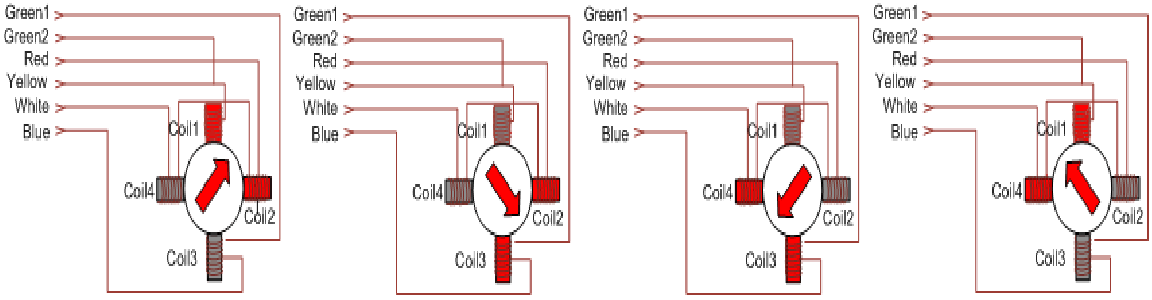


Figure 29- Representation of the Full drive effect on the stepper motor coils (23).

With this method there are always two phases energized at any given time. This full step mode results in the angular movement as wave drive, but the mechanical position is offset by one-half of a full step. The output torque on the motor will be maximized.

III. Half drive

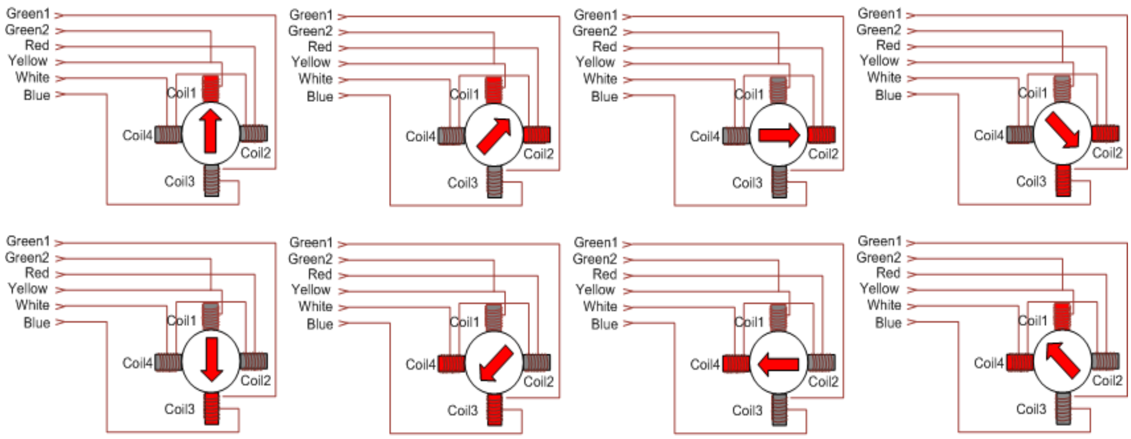


Figure 30- Representation of the Full drive effect on the stepper motor coils (23).

The half drive combines the both methods mentioned before, meaning that the drive alternates between two phases on and a single phase on. But while increasing the angular resolution, the motor will also have less torque available at the half step position because only one phase is energized (approximately 70%). While the two phases are energized the motor will have full rated torque.

The stepping sequences (Table 2) are presented in the following table. Note that the polarity of each terminal is indicated with ± and that in the last step of each sequence it loop again endlessly until indicated by the controller. To change the direction of the motor it is only needed to reverse the stepping sequence.

Table 2- Stepping sequences

Sequence	Polarity	Name
0001	- - - +	
0010	- - + -	
0100	- + - -	Wave Drive or One-Phase
1000	+ - - -	
0011	- - + +	
0110	- + + -	
1100	+ + - -	Full Drive or Two-Phase
1001	+ - - +	
0001	- - - +	
0011	- - + +	
0010	- - + -	
0110	- + + -	
0100	- + - -	Half-Drive or Half-Step
1100	+ + - -	
1000	+ - - -	
1001	+ - - +	

As mentioned, the stepper motor chosen for this particular work is a bipolar stepper motor. It was selected according to the characteristics of a number of existing variables while the operation is running (values of friction between the fuse and the car, weight of the sample holder carrier, torque needed to move, between others) with this values on hand it the Nema 23 motor was selected (Figure 31). Being a usual and standard piece of equipment, it is a component that is easy to substitute or replace if anything should happen to it.

Figure 31- 2-phase stepper motor Nema 23.

On Table 3 is presented some of the most important aspects of the mechanism of the motor (for the entire technical data see Annex E).

Table 3- Technical data of Nema 23 stepper motor (24).

Motor	Nema 23 (distance between hubs 56mm)	
Maximum voltage	[VDC]	60
Nominal voltage	[VDC]	24-48
Nominal current	[A]	4,2
Holding torque	[Nm]	2
Step angle	º	1,8
Max load axial	[N]	15
Max load radial	[A]	52

4.6 STEPPER MOTOR DRIVER

The driver board is solely responsible to receive the signal that is sent from the computer and to treat and amplify these signals in a way that will make the motor turn. For this project we used the Chopper type drive circuit. This circuit provides an optimal solution both to current control and fast current build-up and reversal. Chopper drive circuits are also referred to as constant current drives because they generate constant current (below the nominal maximum voltage of the motor) in each winding rather than applying a constant high voltage. On each new step it will apply a very high voltage (normally several times higher than the nominal voltage of the motor) to the winding activating the motor all as a consequence creating movement. The ratio V_M/V_{supply} is usually called the overdrive ratio (Figure 32).

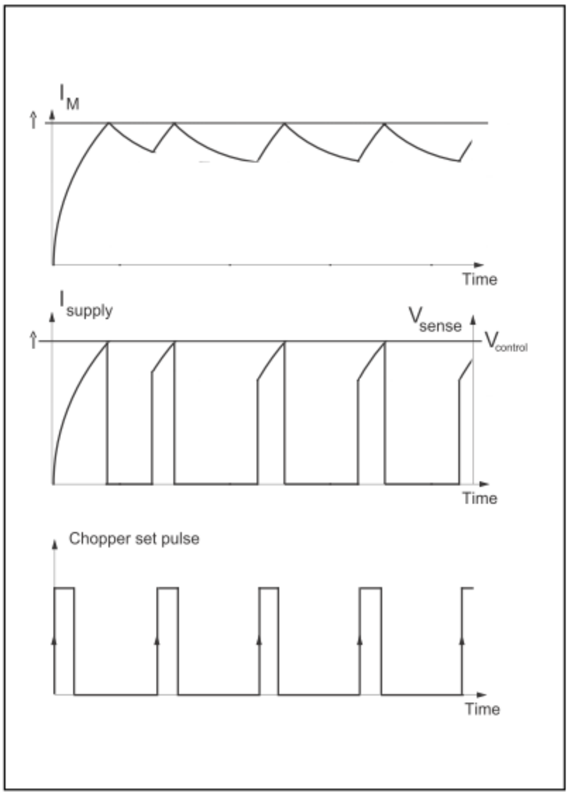


Figure 32- Current waveform in the basic chopper circuit (23).

Constant current regulation is achieved by switching the output current to the windings. This is done by sensing the peak current through the winding via a current-sensing resistor, effectively connected in series with the motor winding. As the current increases, a voltage develops across the sensing resistor, which is fed back to the comparator. At the predetermined level, defined by the voltage at the reference input, the comparator resets the flip-flop, which turns off the output transistor. The current decreases until the clock oscillator triggers the flip-flops, which turns on the output transistor again, and the cycle is repeated. The advantage of the constant current control is a precise control of the developed torque, regardless of power supply voltage variations. It also gives the shortest possible current build-up and reversal time. Power dissipation is minimized, as well as supply current. Supply current is not the same as the motor current in a copper drive. It is the motor current multiplied by the duty cycle, at standstill typically:

$$\mathrm{I}_{\text{supply}} = I_M \times \frac{V_M}{V_{\text{supply}}} \qquad 4.1$$

Depending on how the H-bridge is switched during the turn-off period, the current will either recirculate through one transistor and one diode (path 2), giving the slow current decay, or recirculate back through the power supply (path 3). The advantage of feeding the power back to the power supply is the fast current decay and the ability to quickly reduce to a lower current level. One example is when microstepping at a negative slope, which may be impossible to follow if the current decay rate is lower than the slope demands. The disadvantage with fast current decay is the increased current ripple, which can cause iron losses in the motor.

The stepper motor driver has three main components being them the L297 and L298N integrated circuits.

4.6.1 Integrated Circuit L297

The L297 IC is a stepper motor controller that generates four phase drive signals for two phase bipolar and four phase unipolar step motors in microcomputer controlled applications. This controller enables the user to drive the stepper motor in every drive described before and on chip PWM chopper circuits permit switch-mode control of the current in the windings of the motor. One advantage of this particular integrated circuit is that to work it only requires the clock, direction and mode input signals. The phase signal is generated internally reducing consequently a heavier use on the microcontroller and it simplifies the coding for the programmer. Mounted in DIP20 and SO20 packages, the L297 can be used with monolithic bridge drives such as the L298N or the L293R or even discrete transistors, mosfets and darlingtons. In the Figure 32 and in the Figure 33 can be seen the L297 real representation and the pin connections, respectively.

Figure 33- Integrated Circuit L297.

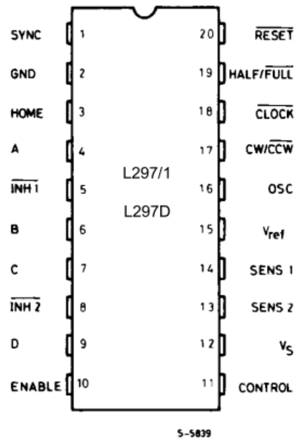


Figure 34- L297 Pin connection (Top view)

4.6.2 *INTEGRATED CIRCUIT L298N*

The integrated circuit L298N has inbuilt a high current dual full-bridge and its main objective is to drive inductive loads such as relays, solenoids, DC and stepping motors. It is a high voltage part, but it can also be activated with a few milivolts, to the maximum voltage range of 45V. It also has two pin connections that enable the monitoring of the current circulation that the motor is consuming (Pins SENSE-A and SENSE-B), by receiving the given information of the consumed current. With the L297 it is also possible to control the current by limiting using a potentiometer. For each one of the four outputs it can give an current as high as 2A or as peak current a maximum of 4A.

This device is also known for overheating while working at high voltages and high current. Given that the motor works at 24V and 4A it is need to fabricate an heat sink made of aluminium and a fan to keep the temperature within the working range temperature of the L298N (it situates itself in the range of -25 °C to 130 °C at the absolute maximum ratings). In the Figure 35 and Figure 36 can be seen the L298N real representation and the pin connections, respectively.

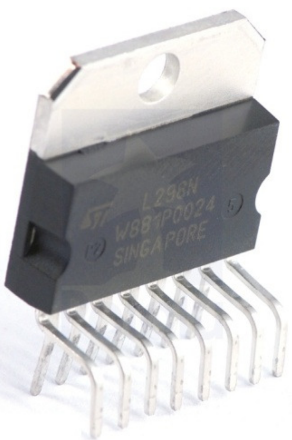


Figure 35- Integrated Circuit L298N.

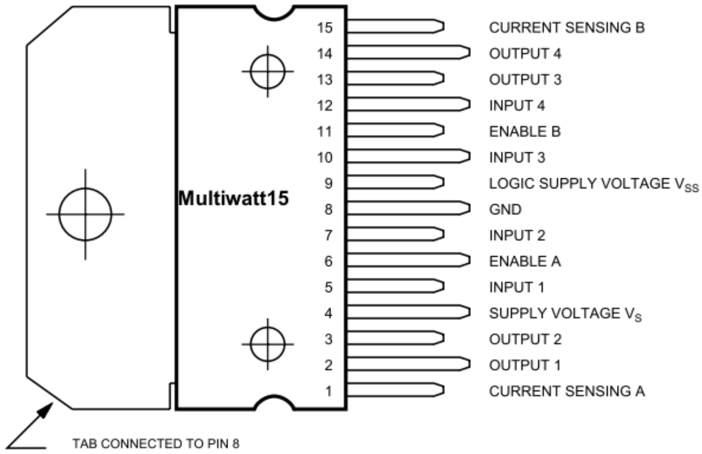


Figure 36- L298N Pin connection (Top view)-

Although the usual circuit seen while combining L297 and the L298N (Figure 37) integrated circuits is widely used as a stepper motor drive in this case it cannot be used given the high, because as referred before the maximum current output per output is of 2A.

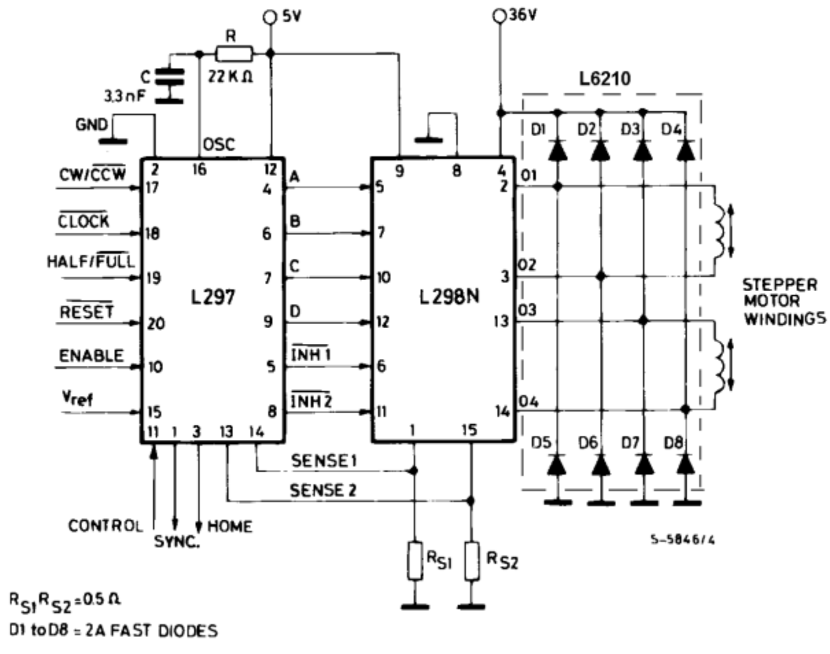


Figure 37- Two phase bipolar stepper motor control circuit.

To counter this limitation of the L298N it has decided to implement a change in how the circuit works.

The L298N device possess two separate channels (Output 1 and 4, and Output 2 and 3), each one capable of driving 2A current loads, so by connecting them in parallel it is possible to drive the motor with inductive loads up to 4A continuously because it will become a single 4A integrated circuit driver, this can be achieved by following the circuit as seen on Figure 38.

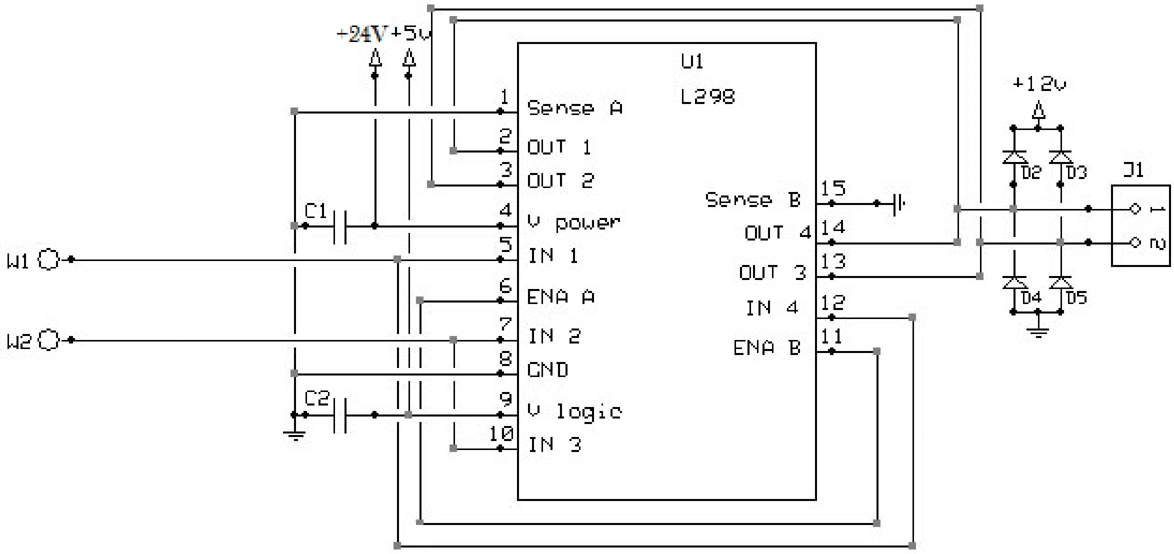


Figure 38-Circuit of L298N integrated circuit as a 4A single driver.

Being, W1 and W2 the one of each pair of outputs of the L297 device and J1 one of the windings in the motor. As referred before by using this implementation it is required a second L298N device in order to connect to the second pair of outputs of L297 and the second winding on the motor

4.7 EIA-232 DRIVER/RECEIVER

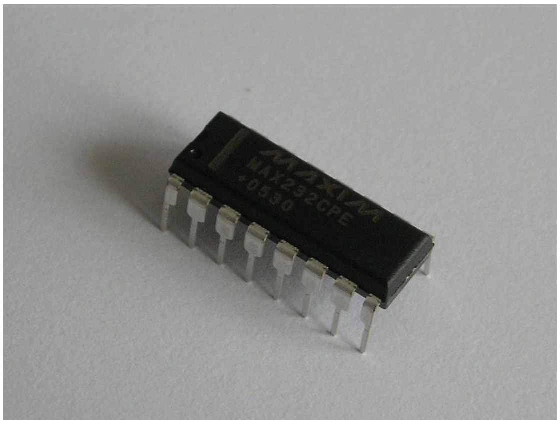


Figure 39-Integrated circuit Max232.

The MAX232 is an integrated circuit that converts signals from an RS-232 serial port to signals suitable for use in TTL compatible digital logic circuits. The MAX232 is a dual driver/receiver and typically converts the RX, TX, CTS and RTS signals.

The drivers provide RS-232 voltage level outputs (approx. ± 7.5 V) from a single + 5 V supply via on-chip charge pumps and external capacitors. This makes it useful for implementing RS-232 in devices that otherwise do not need any voltages outside the 0 V to + 5 V range, as power supply design does not need to be made more complicated just for driving the RS-232 in this case.

The receivers reduce RS-232 inputs (which may be as high as ± 25 V), to standard 5 V TTL levels. These receivers have a typical threshold of 1.3 V, and a typical hysteresis of 0.5 V.

4.8 LINEAR TABLE

A linear table (which is also known as a X-Y table) helps to provide the horizontal motion needed to accomplish the work at hand. This table allows movement on the basis of the sample holder along the X axis (distance). The linear movement is performed with trapezoidal nuts which are driven manually or with the use of a motor, as is done in this work.

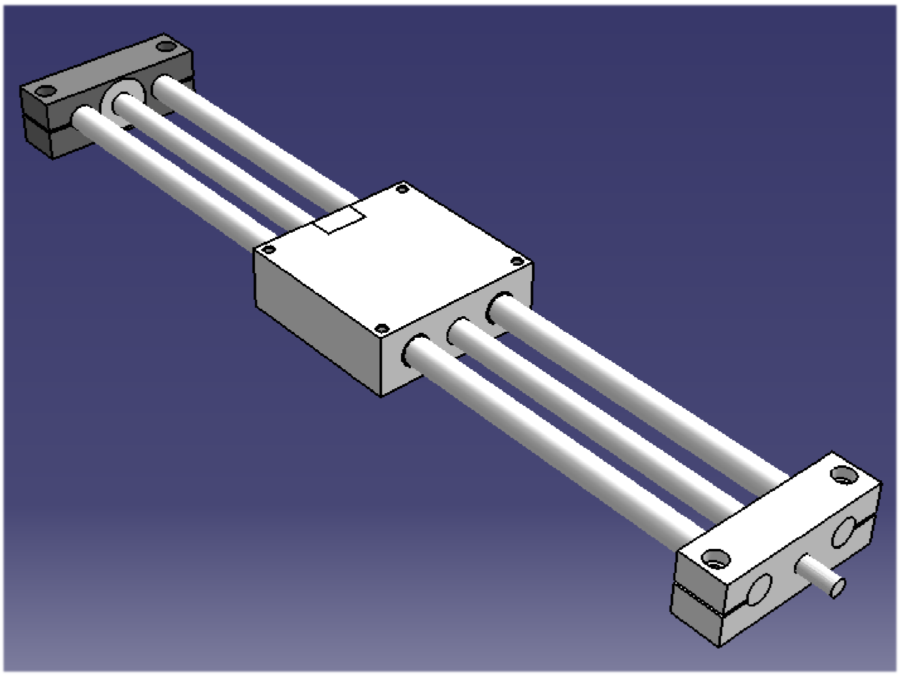


Figure 40-Cad representation of linear table (Igus).

The 3D cad drawing of the linear table is represented in the figure above. This linear table was acquired from IGUS and it belongs to the series SHT.

The table was chosen considering the weight of the sample holder, speed of the movement, strength needed to move the trapezoidal nut and the precision of the positioning.

The maximum weight of the sample holder was projected to have a maximum value of 10Kg, even though the weight of the sample holder is far away from this maximum the linear table was chosen thinking on future works requiring a heavier load. The deflection (term that is used to describe the degree to which a structural element is displaced under a load) under a load of 10Kg is of 0.75mm. In the Figure 41 the F1 force represents the 10kg load and the x the deflection suffered by the linear table.

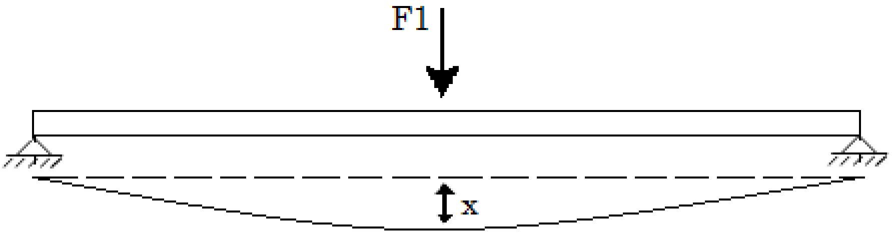


Figure 41- Beam deflection under a load.

More details about the linear table can be found in the Annex D.

4.9 FURNACE

The furnace acquired to full the demands of this work is the one on the Figure 42.

Figure 42-Cylindrical Oven.

With this furnace it is possible to control both maximum temperature and the rate of heating. It is a cylindrical oven with two entries (both sides are open enabling the sample holder to enter from either side) as can be seen in Figure 43.

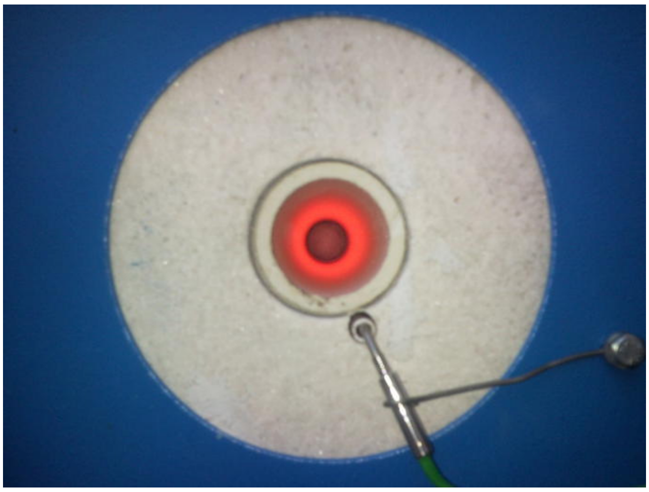


Figure 43-Entry point of view of the oven.

One of the objectives successfully obtained with this furnace is the nullification of the electromagnetic forces while not obtaining a long hot zone while maintaining the required gradient of temperatures (the dispersion of the temperature is not homogenous) on the ceramic cylinder. This fact can be also seen on the Figure 43 by noting the increase of the temperature with the higher distance.

The heating is produced by a resistor constructed with Kanthal A1 wire. It has 3.75mm of diameter. The power supply of this resistor is one with low voltage. The total dissipated power output by the heating element has a maximum value of 1.200 W.

Figure 44-Ceramic cylinder connected to the Kanthal A1 wire.

In the Figure 45 it is possible to observe a simplistic interpretation of how this product (Ceramic cylinder plus the Kanthal A1 wire) is inserted in the oven.

The tube has a length off 450mm and the Kanthal A1 wire surrounds the ceramic material with a total length of the 300mm, the diameter is of approximately 38mm.

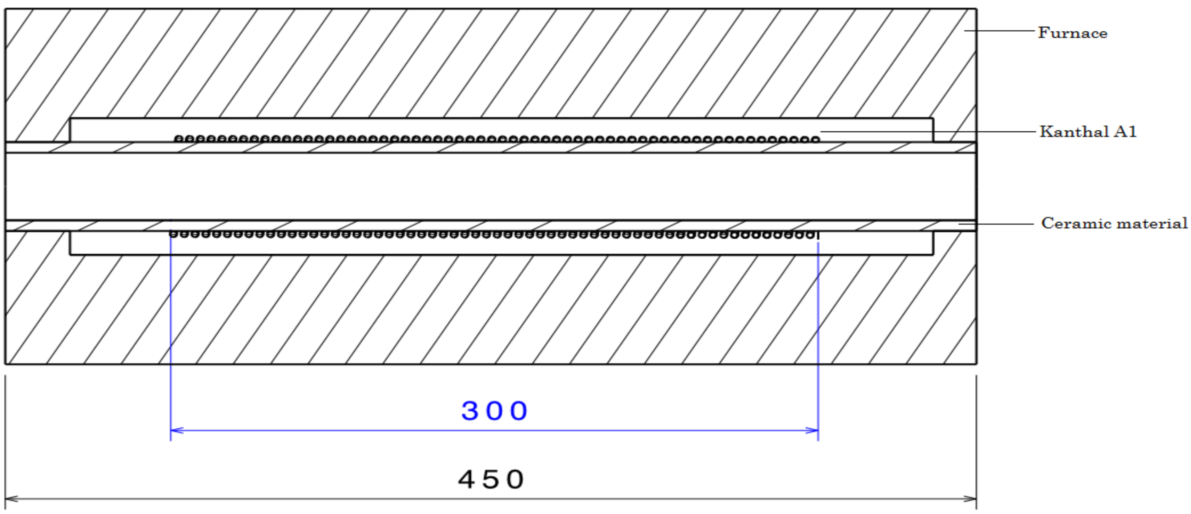


Figure 45- Drawing of the furnace

4.9.1 THERMOCOUPLE / MAXIM MAX31855 IC

To measure the temperature of the sample holder a thermocouple of the type K is used. This thermocouple can read temperatures that belong to the range of -180 °C to 1300 °C.

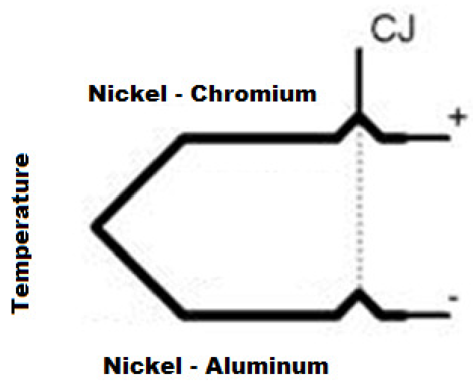


Figure 46- Thermocouple Type K

The thermocouple is connected to an integrated circuit ("IC") with designation max31855. The max31855 is an IC that performs cold-junction compensation and digitalizes the signal from the thermocouple it is connected to. The output data from this IC has the format describe on Table 4.

Table 4-Output data from Max31855 (25).

	14-Bit Thermocouple Temperature Data				RES	Fault Bit	12-Bit Internal Temperature Data				RES	SCV BIT	SCG BIT	OC BIT
Bit	D31	D30	…	D18	D17	D16	D15	D14	…	D4	D3	D2	D1	D0
Value	Sign	MSB	…	LSB	Reserved	1 = Fault	Sign	MSB	…	LSB	Reserved	1= Short to VCC	1 = Short to GND	1 = Open Circuit

It is a signed 14-bit, SPI compatible, read-only format.

the maximum temperature allowed by this IC is 1800 °C (far above the maximum required by this project, approximately +- 1250 °C) being the minimum -270 °C, it resolves temperatures to 0.25 °C. The accuracy of the measurement of the temperature for temperatures ranging from -200 °C to +700 °C is of +-2 °C and from 700 °C to 1300 °C the range being +-4 °C.

Having the Serial peripheral interface bus (also known as "SPI") implies that we have a master/slave combination; the master is the Pic16f877 and the slave the IC max31855. This interface is a serial data link that operates in full duplex mode. The master device is the one to start the transmission of data.

To measure the temperature of the sample holder a thermocouple of the type K is used. This thermocouple can read temperatures that belong to the range of -180 °C to 1300 °C

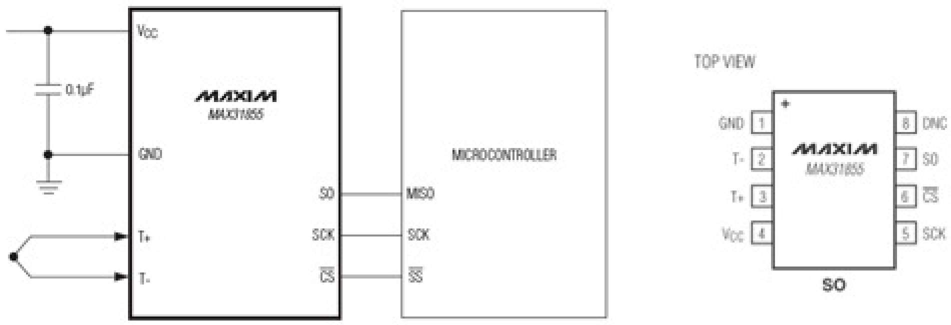


Figure 47- Amplifier Max31855 (25).

4.10 MECHANIC EQUIPMENT

As it was referred previously the samples are inserted in the furnace via a cylindrical bar of Alumina. The bar needs to be hollow to insert the thermocouple and the fiberglass cotton to encompass the samples. The outer diameter must also be large enough to sustain the samples while not touching the walls of the furnace to not jeopardize the furnace, the experimental tests or even the alumina bar.

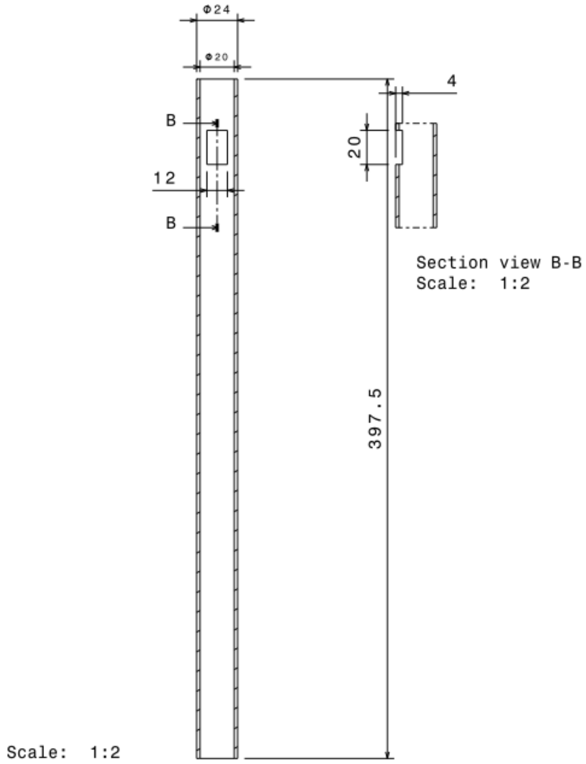


Figure 48 - technical drawing of the alumina bar

Figure 49 – Alumina bar with fiberglass cotton

To allow simple assembly/dismantling the linear guide does not have a support beneath it, instead it was developed in a manner to allow the movement on the Z axis (height) to adjust the height of the center of the alumina bar with the center of the furnace.

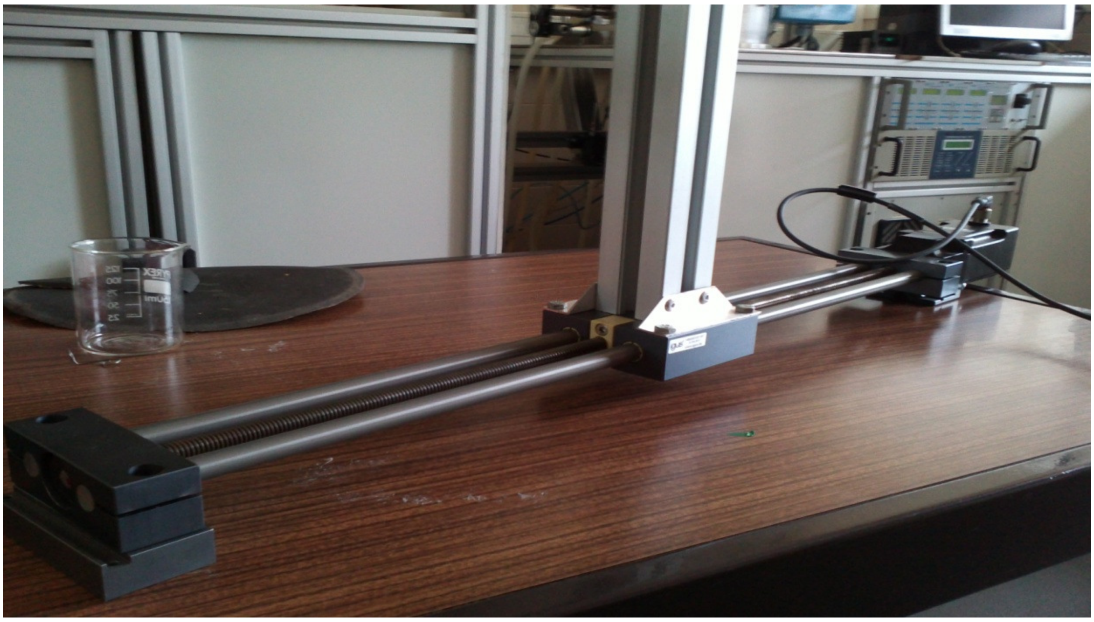


Figure 50 – Linear guide with the support for the alumina bar

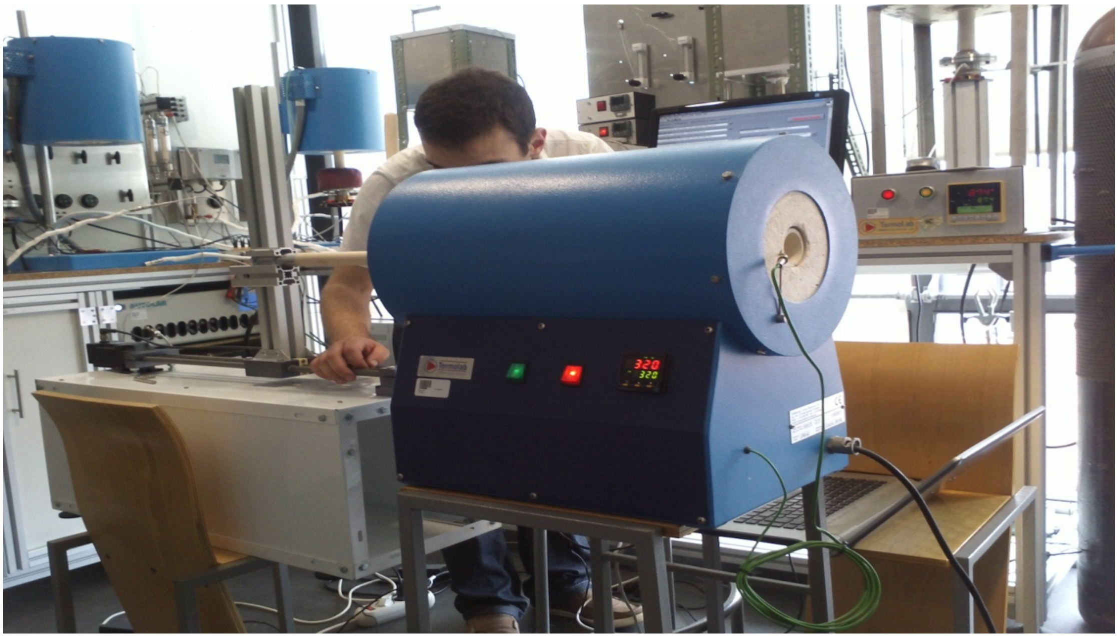


Figure 51 – Photo taken during an experiment test

4.11 LIST OF MATERIAL USED ON THE INSTRUMENTATION CIRCUIT

The following figure represents the electronic material used on the Project.

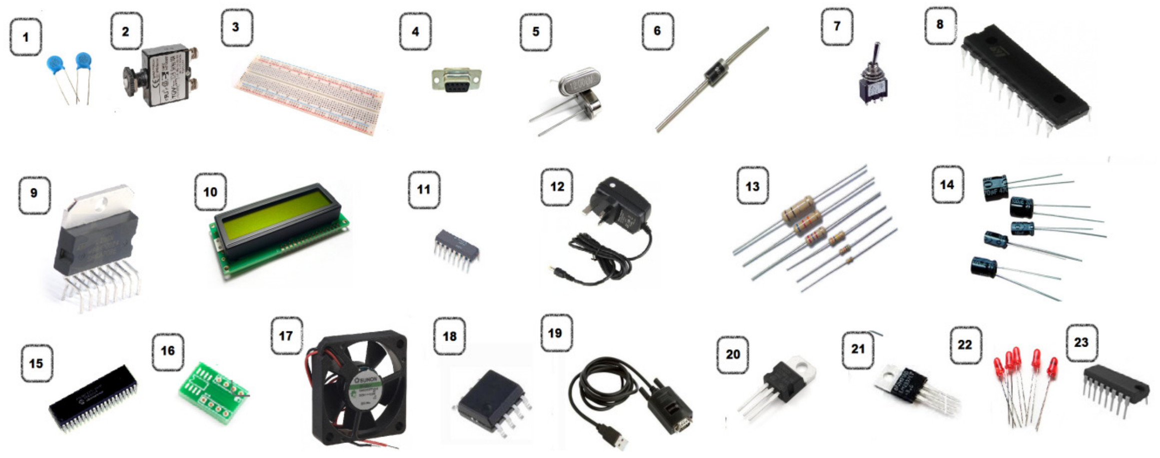


Figure 52-Material used on the electronic circuit of the developed work.

Numeração / Componente	Componente escolhido
1. Ceramic capacitor	0.1 uF 100 uF 100uF 22pF
2. Button	Button Normaly open
3. Breadboard	Breadbord is a construction base for prototyping of electronics
4. DB9	Subminiature electrical connector.
5. Electronic oscillator	Electronic oscillator of 4 MHz.
6 . Diode	In4007
7. Interruptor	Interruptor normally open

8. Stepper motor controller	L297 IC stepper motor controller
9. H-Bridge IC	L298 H-Bridge to control step motors
10. LCD 16*2	Liquid crystal display 16 characters, 2 lines
11. Signal amplifier	Integrated circuit that converts signals from an RS-232 serial port to signals suitable for use in TTL compatible digital logic circuits.
12. Power Supply	Power supply of 20Vdc
13. Resistor	1kOhm 100ohm 20kOhm
14. Polarized capacitor	100uF 470uF
15. Microcontroller	PIC16f877a microcontroller.
16. A*daptator*	Adaptator SOIC8[a] for DIP[b] to use the MAX6675 in a breadboard.
17. Fan	5V Fan
18. Signal amplifier	Thermocouple type K amplifier Max31855.
19. Convertor cable	Rs232 to USB cable converter
20. Positive voltage regulator	Continuous corrent regulator a 5V LM7805.
21. Positive voltage regulator	Continuous corrent regulator a 3.3V LM2937-3.3-ET.
22. Leds	Light emitting diodes
23. Level Shifter	Voltage level shifter 4050

4.11.1 *PROGRAMMING*

For the programming of the microprocessor was used MPLAB ID v8.56 with the compiler Hi-Tech Pro Lite.

The C programming language was used to develop the program needed to accomplish the tasks that this dissertation demands.

MPLAB uses by default the assembly language; afterwards it would translate the code into numerical values for the PIC (hexadecimal).

But this language is specific to each device, which means that each program becomes obsolete the moment the microcontroller families is changed, this is the main reason that was opted to use C language being it general-purpose programming language that can work on any microcontroller that has a C compiler working for it.

The C language has also more programmers and a better library to gather research, this allows changes more easily to be made to the microcontroller we are using and to give it more flexibility and specifications that are not used in this dissertation.

The only fault while programming with C language is the memory which it occupies within the microchip. This is one of the limits of this device. The low memory the programmer as allocated to code, means that the memory allocation on the microchip is not fully optimized. This is one problem we would not have using the assembler language, but the memory given on the PIC16F877 is enough for the coding necessary to fulfill the task at hand.

Hi-Tech Pro Lite is a C language compiler, this software is free to use and it optimizes ANSI C language. This compiler supports all microchip in this range PIC10,PIC 12 and PIC16 devices.

The compiler is also available on a number of popular operating systems such as Windows (32 and 64-bit), Linux and Apple OS X.

Being this the free version of the Hi-Tech compiler it does not make use of the Omniscient Code Generation (OCG) technology, it improves the compilation of the code to a degree of 40% reduction of memory allocation on the microcontroller. This allows future uses of the code generated for this purpose to be expanded for future uses by upgrading to the licensed version of Hi-Tech Pro compiler.

The elaboration of the circuit passed through a variety of steps to the final condition.

1) Manual control

2) Thermocouple value input

3) LCD integration

4) Encoder programming

5) Rs232 connection

6) Automatic control

The **manual control** of the stepper motor was created to enable the user to control the position of the sample holder without having to use the computer (Visual Basic application). Nonetheless, the information regarding the temperature and the position of the motor will still be sent to the computer and the LCD, enabling the user to have a basic understanding of the system parameters. The movement is defined by an interrupter that creates an ON/OFF setting and an additional button that creates the CW (Close Wise) or CCW (Counter Clock Wise) movement of the stepper motor to reproduce forward or backwards movement of the sample holder. Using this option the speed of the motor is predefined and cannot be changed.

The second step will allow the use of the thermocouple to evaluate the actual temperature of the samples.

The LCD is used in this circuit to enable the user to have real time surveillance over the variables of the position of the sample holder and temperature of the samples the sample holder is carrying. It is used and LCD of 16 digits per line, having the LCD a maximum of two lines. It will display the values like demonstrated on the Figure 54.

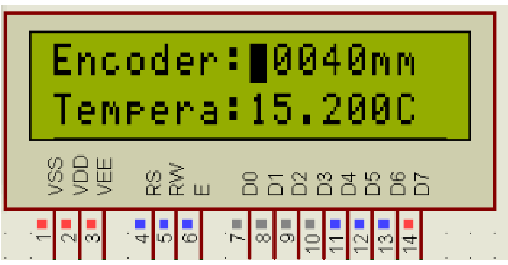


Figure 53-LCD simulation provided by ISIS Proteus

A new architecture was used on this particular LCD this means that this LCD already uses the ROHS architecture implemented since 2006. The difference between versions is that we need to switch on a transistor (PortD pin 7) to power up the LCD module; this is embedded within the code.

The position of the sample holder is known by creating a counter in each step the stepper motor does (as explained before on the working of the motor).

To control and be able to move at various different sets speeds and ramps the sample holder it is used the RS232 standard connection with a computer that would then connect to a Visual-Basic application that would make the necessary calculations between the temperature and current position of the sample holder to create the ratio of speed or movement wanted on the stepper motor.

Automatic control was the last step to be made because it needed all the other functions working. This function will allow the user to program a given set of instructions (Speed ratio and/or direction) without having to actually control the motor manually. In this step the connection between the microcontroller and the computer cannot be stopped.

There are major differences embedded in the code between the two types of work (Speed ratio or direction). By using the first type, the control of the velocity is achieved by changing the delay between the steps which will influence directly the velocity the motor is running. The application on the computer would gather the information given by the thermocouple to determine either it should faster or slower, and then send the information to the microcontroller. The following code example will explain how this was achieved.

```
Input= Getch();  // received information over Rs232

RB1=1;                                          //  Enable stepper motor
RB0=1;                                          //  Direction given to the stepper motor
        for(i = 0; i = input;i++)

{
        RC0=1;                                          //  Stepper Clock
        __delay_ms(1);                                  //
        RC0=0;                                          //
        __delay_ms(1);                                  //   StepperClock
        Position_Counter= Position_Counter +1;          //   Position Counter

}                                                       //  End For
```

By using the direction type of control, the speed would be at constant value but the direction would be changed according to the needs. The control would still be using the application on the computer to be able to identify either the motor should be moving clock wise or counter-clock-wise. The movement would be controlled only by the type of ramp set by the user, meaning that when the temperature read by the thermocouple would surpass the indicated value the application would send an order to the control to move the sample backwards while the temperature is not below the value it should be at. This loop will continue until the allowed temperature increases, by then the motor will keep moving forward while the temperature does not surpass once again the set value. The following code example will explain how this was achieved.

```
if (RE1 == 0){

    if(RCIF) {                      // Receive Data from rs232, use of interrupt
        input= getch();             // read a response from the user
        Dir=input-0x30;             // Conversion from Ascii to Decimal numbers
        }

        else
        {
        __delay_ms(1);          // Does not receive data from rs232, continues program
        }
        if (dir==2){
        RB0=1;                      // Direction given to the stepper motor

            RC0=1;
            __delay_ms(5);
            RC0=0;
            __delay_ms(5);
            Position_Counter= Position_Counter +1;
        }                           // End input ==2
        if (dir==1){
        RB0=0;                      // Direction given to the stepper motor
            RC0=1;
            __delay_ms(5);
            RC0=0;
            __delay_ms(5);
            Position_Counter= Position_Counter -1;
        }                           // End input ==1
        if (dir==3){
            RB1=1;                  // Disable stepper motor
        }                           // End input ==3
}                               // End RE1 Off
```

The flowchart presented on the Figure 55 explains how the program works.

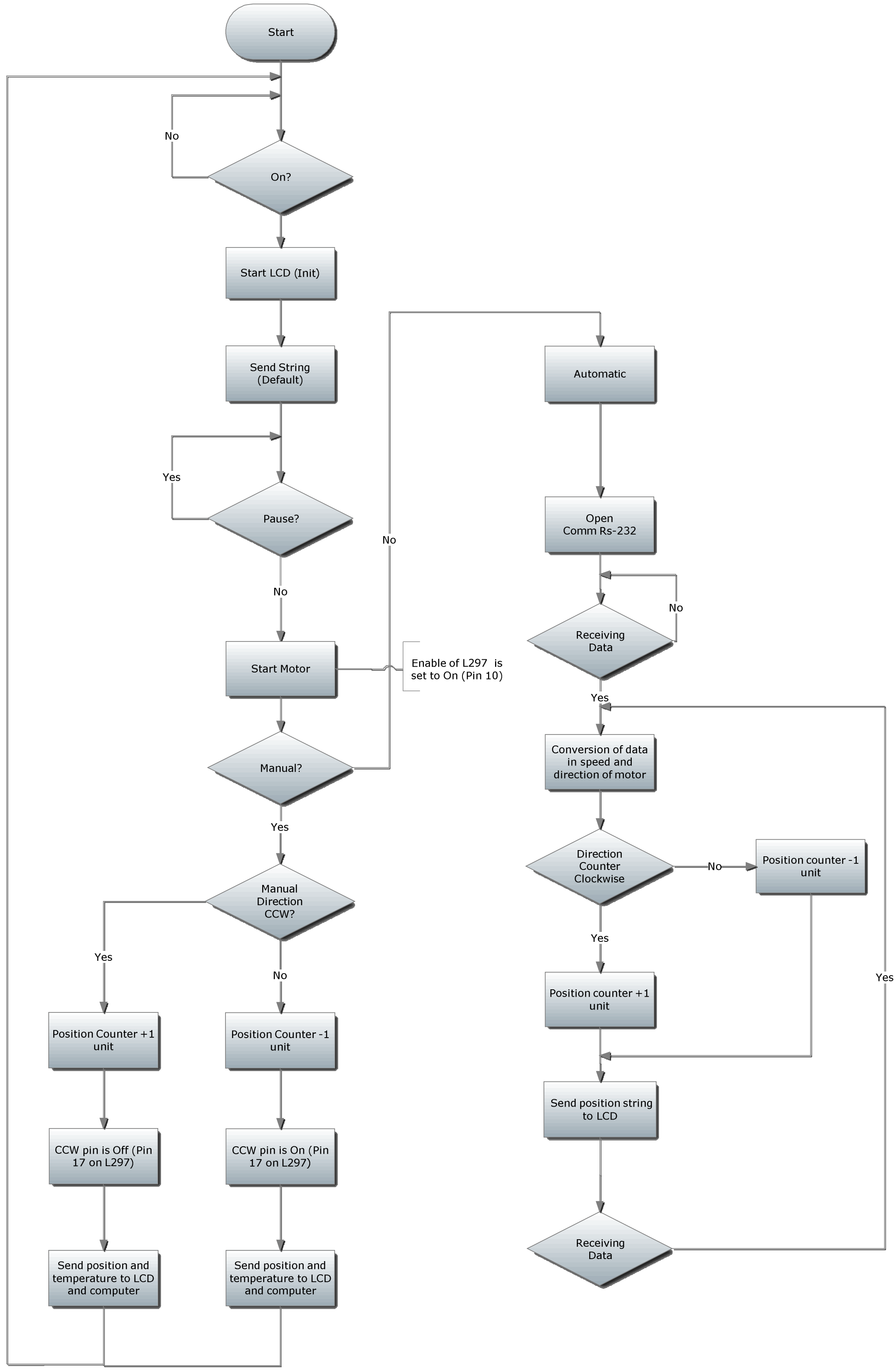


Figure 54- Flowchart.

4.12 ASSEMBLY OF THE ELECTRONIC EQUIPMENT

The control box elaborated for this project is presented on this subchapter.

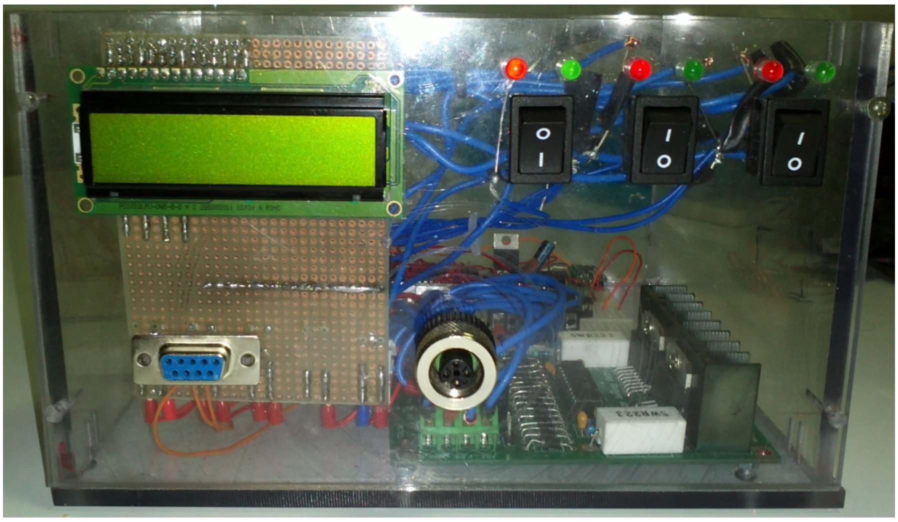


Figure 55 – Frontal view of the control box

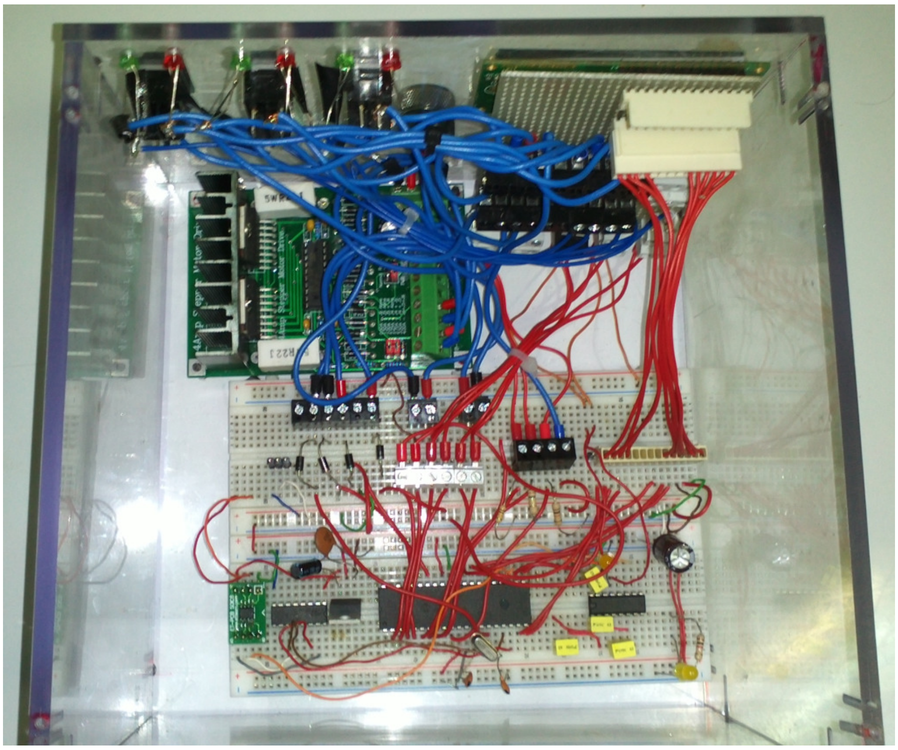


Figure 56 – Top view of the control box

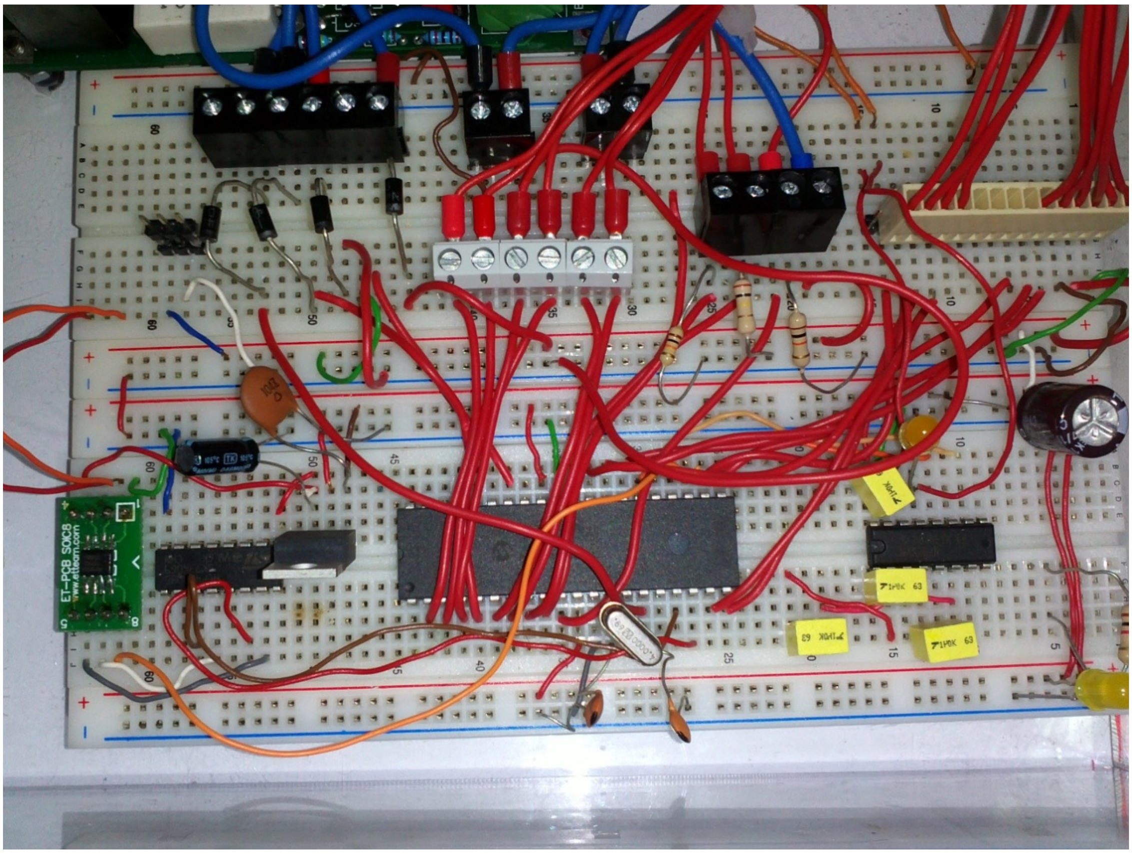


Figure 57 – Detail view of the electric circuit

4.13 Visual Basic Application

The main focus on the prepared visual basic application was to elaborate a clean user interface (“UI”), while maintaining the functionality of the same.

In the application the user is able to visualize the position and temperature at all times when connected to the microcontroller.

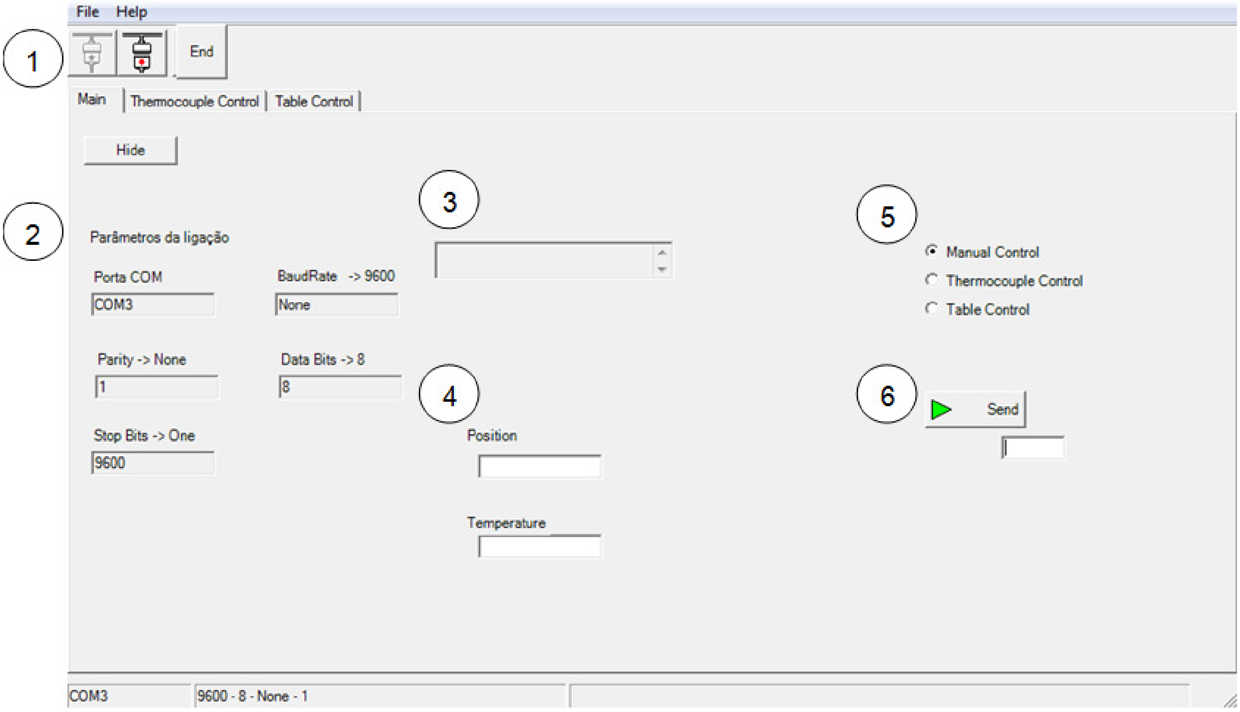


Figure 58- Main control tab

In the Figure 59is presented the main page of the interface, where:

1- Open settings menu , Connect/Disconnect

2- Active connection parameters

3- Display of the string received by the microcontroller

4- Display of the position and temperature

5- Operation mode selection

6- Manual control of the direction of the motor

The operation mode selection allows the selection of three modes of operation;

4.13.1 MANUAL CONTROL

This mode allows the user to control the direction freely at a constant velocity. Although this mode is called Manual control, the microcontroller needs to be set up as automatic control since the control is still not been given directly by pushing buttons but by sending information over the connection between the microcontroller and the computer. This mode work by sending a string telling the microcontroller in which direction it should move.

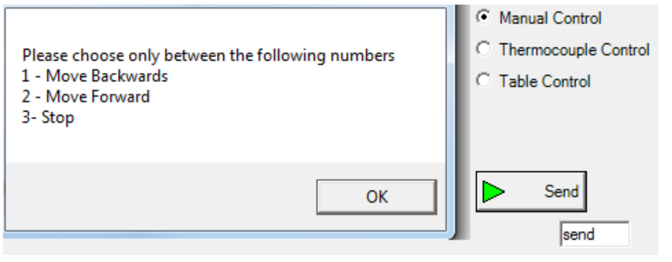


Figure 59- Detailed screenshot of error/information shown when manual control is selected.

The Figure 59 shows the error that will pop up if the right order isn't entered in the text box, the error will also explain what needs to be written to start the movement of the motor.

4.13.2 THERMOCOUPLE CONTROL

This mode allows the user to insert the ramp of heating desired but the velocity will be given a constant value as explained before.

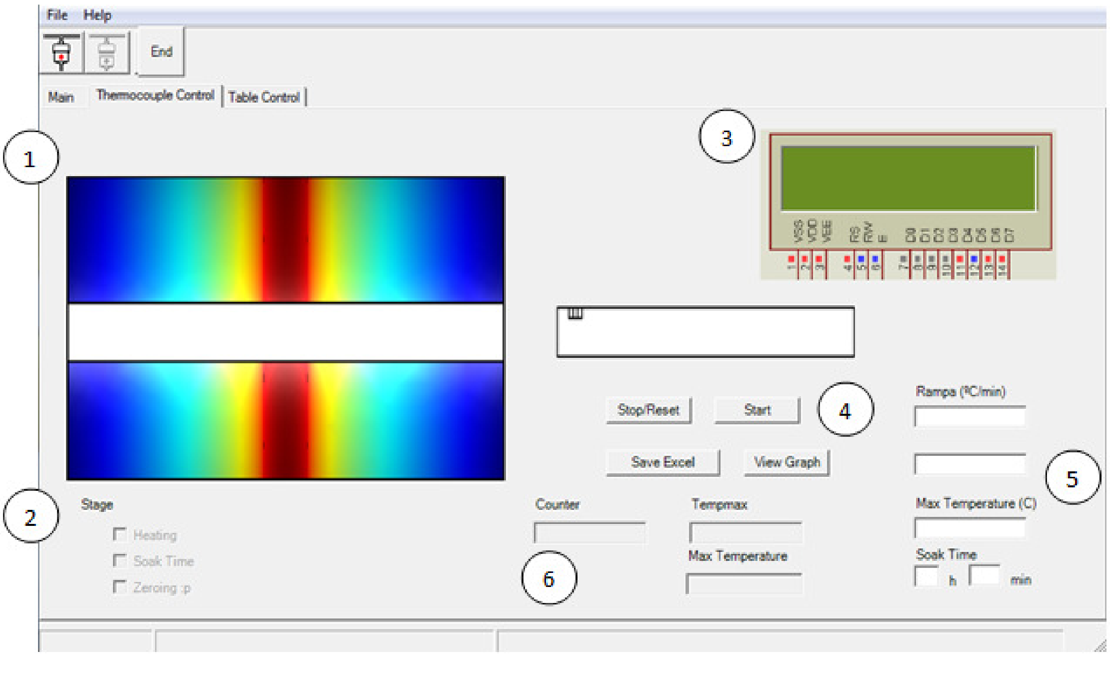


Figure 60- Thermocouple control tab.

The Figure 60 presents the main page of the interface, where the numbers signify:

1- Furnace and sample holder

2- Stage of sintering indicator

3- Display of the position and temperature

4- Command Buttons

5- Input Settings

6- Information Display

A visual aid was implemented on the representation of the furnace and sample holder for the user to help observe where the sample holder is in the furnace, since it will move accordingly to the position it is given by the microcontroller. Of course this feature will only work with this particular furnace or with one of a similar geometry. The stage of sintering indicator will indicate whether the sintering is still on the heating process, the soaking time inside of the furnace or if the sintering process is complete and the sample holder is returning to the point of origin. The command buttons allows the user to start the sintering process, stop it, view the graphical representation of the last experimental test and it can also save or not the test. The input setting allows the choosing of the heating ramp, the soak time and the desired temperature to be reached. The information display shows the time spent on the test, the temperature to be reached, and the maximum temperature selected by the user.

5 RESULTS

Experimental tests were performed at different furnace temperatures and different heating rates. The method used in the experiments was, for any given constant motor velocity, to follow a sintering ramp with the closest possible fidelity. This was accomplished by changing the motor direction whenever it was required to increase or decreased the temperature. The graphics show the relationship obtained between the temperature and the time for any specific heating rate, represented in red.

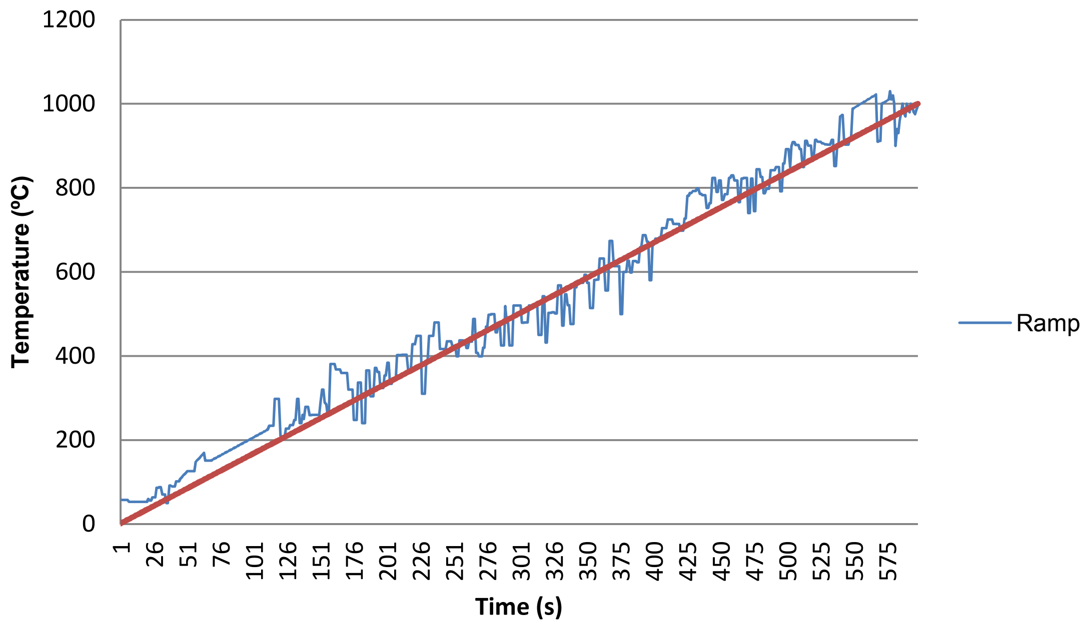


Figure 61- Graph obtained with a ramp of 100°C/min, at 100mm/min and the furnace set at 1000°C

Figure 61, shows a reasonable agreement between sample temperature and desired ramp rate for a fast firing ramp rate of 100ºC/min. Nonetheless, one can observe fluctuations in temperature of the order of ±100ºC around the intended temperature values. These temperature fluctuations arise due to slow heating and cooling of the surrounding alumina sample support tube due to its low thermal conductivity. This is discussed further in the conclusions. Control is also observed to be difficult at the lowest temperatures due to low temperature gradients at the mouth of the furnace and, thus, the greater influence of the ambient air temperature and drafts. This low temperature deviation is observed to be more severe at high ramp rates, Fig.63.

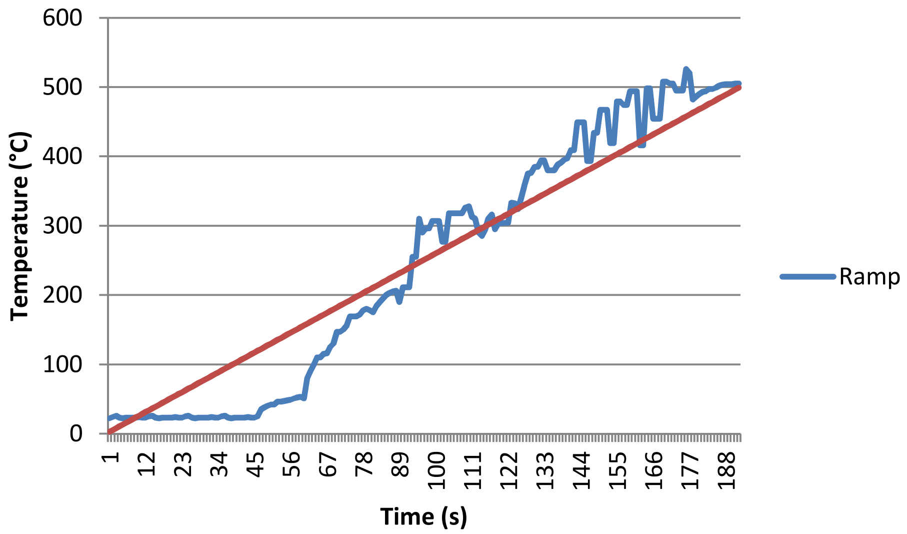


Figure 62 - Graph obtained with a ramp of 150°C/min, at 50mm/min and the furnace set at 500°C

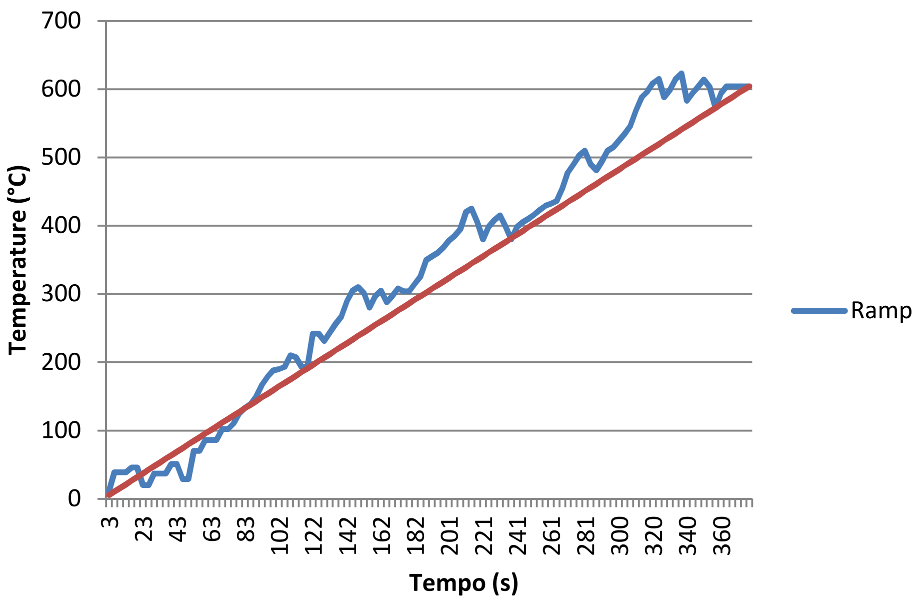


Figure 63- Graph obtained with a ramp of 100°C/min, at 50mm/min and the furnace set at 600°C

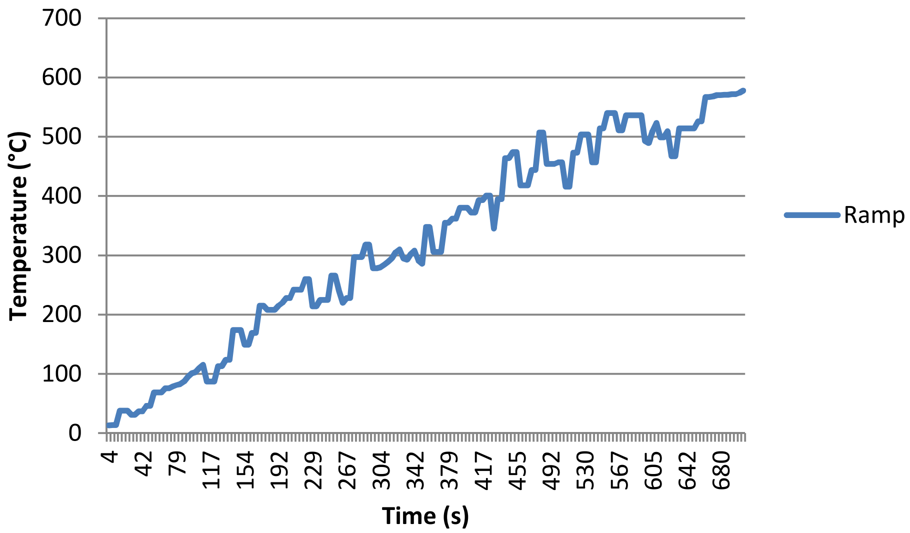


Figure 64 - Graph obtained with a ramp of 50°C/min, at 100mm/min and the furnace set at 600°C

The results obtained show the importance to tailor the control variables during the ramp to achieve the most accurate response. During an experiment we can change various sintering options such as (Temperature of the furnace, velocity of the insertion of the samples and the ramp desired).

6 CONCLUSION

The work accomplished in the scope of this thesis, had as the objective of the Conception of a system that allows the sintering of samples on any given tubular furnace, with different displacements, different gradients of temperatures and different working conditions.

For the development of this work it was necessary to choose a set of equipment that allowed the fulfillment of the task at hand, the development of the programs and the methodology and to test and validate through experimental tests and analysis.

One of the crucial aspects of the described project on this thesis was the selection of the method of control of the motor while reading/analyzing the temperature. Some constrains were cost, reliability of the results and the possibility of having a permanent and fast connection between the computer and the circuit.

All of the selected components follow the above principle and are within the scale of work being it temperature level or speed of analysis and to highlight the possibility of having the possibility to also control the position manually and having an instant feedback, this fact also adds a new layer of security and use to this project.

The control system developed contains an intrinsic error in the reading of the temperature of 0.25 °C and this only represents and error off 0,02% to 0,025% on the operative scale of the temperatures to be used on this particular work that goes from 1000 °C to 1200 °C (note that the temperature range can go from a minimum of 100ºC to a maximum of 1350 °C, with 100 °C being the lowest temperature to do a valid operation with the program and the 1350 °C the maximum temperature the IC max31855 can read). The monitoring of the temperature on manual setup is done in an interval of 500 milliseconds and while on operation of 1second to avoid any errors of communication between the microcontroller and the amplifier of the thermocouple.

The results show that the starting point of the sintering process shows great discrepancies on the temperature values gathered, due to the already mentioned ambient temperature fluctuations which went from 15 °C to over 30 °C caused by drafts and in addition the low temperature gradient at the mouth of the furnace.

The thermocouple cooling also affects in some degree the readings of the temperature. When the thermocouple is placed inside the alumina cylinder that carries the samples the value of the temperature takes longer to decrease/increase because it depends directly on the ability of the alumina material to follow the heating/cooling process. For more accuracy a support material of higher thermal conductivity is, therefore, needed.

By increasing the temperature over 600 °C the resolution required on the position is below 1 millimeter, because the temperature changes much more quickly as the thermocouple starts to get near to the core of the furnace.

The project, therefore, accomplished the objectives. However, fine tuning of the control is still needed with respect to motor speed and thermal conductivity of the support tube.. The operation can reach temperatures has high as 1350 °C, with sufficient speed to enable sintering rates from 50ºC per minute to 150 °C per minute with a reliable response given the conditions of the experimental tests. The selected components proved to be appropriate to achieve the functional conditions desired. The circuit offers an acceptable level of precision and works with consistency with the Visual Basic application created for this work.

7 FUTURE WORKS

Since the continuity of the work presented on this thesis possess a high interest, at this point are provided some suggestions and tasks to enhance the project.

i) More tests at more specific rates of sintering to determine which control parameters are needed for which furnace temperatures and ramp rates. For example, additional parameters can be altered such as changes of backwards speed to attempt to compensate for the slow cooling of the support tube. With this improvement the relation Temperature/Time may possibly be improved.

ii) The addition of a second thermocouple that will move at the same time the thermocouple checking the temperature of the samples. This second thermocouple will be placed in front of the sample holder to read the temperature and store it the visual basic application. This will change how the program functions, because instead of relying on direction changes at a constant speed, it will work with variable speeds calculated with the displacement between the temperature taken by the second thermocouple and the sample holder one.
The second thermocouple can be applied to the already made circuit, because this concept has been predicted for future works and the code to read two thermocouples simulatiously has already been implemented in the code.

iii) The implementation of a Wifi or Bluetooth component to enable the working of this circuit without it needing to be near the either the circuit or the furnace.

iv) If the same furnace is used for a long period of time it could also be create an array of data between the temperature/position to determine the exact velocity at any point of the motor to conduct a more reliable experimental test. This method was not implemented in this work, because the main idea was the ability to change the furnace that the sample is supposed to be sintered with, without the need to make additional changes to the code either in the microcontroller or in the Visual Basic application.

8 REFERENCES

1. Gitzen WH. Alumina as a Ceramic Material. The American Ceramic Society; 1970.

2. Herring C. No Title. J. Appl. Phys. 1950;21:301–303.

3. Rahaman MN. Ceramic processing and sintering. Marcel Dekker; 2003.

4. Coble RL. No Title. J. Appl. Phys. 1961;32:787-792.

5. Barsoum MW. Fundamentals of ceramics. Taylor & Francis; 2003.

6. Frenkel J. No Title. J,Phys. (Moscow) 1945;5:385.

7. Shi JL. Solid state sintering of ceramics : pore microstructure models , densification. 1999;di:3801 - 3812.

8. Uhlmann, D. R. Klein, L. C. Hopper RW. No Title. Dordrecht, Holland 1975;277–284.

9. Esposito V, Traversa E. Design of Electroceramics for Solid Oxides Fuel Cell Applications: Playing with Ceria [Internet]. Journal of the American Ceramic Society 2008 Apr;91(4):1037-1051.[cited 2010 Aug 25] Available from: http://doi.wiley.com/10.1111/j.1551-2916.2008.02347.x

10. Y. M. Chiang, D. Birnie III WDK. . In: C. Robichaud KS, editor. Physical Ceramics, Principles for Ceramics and Engineering. New York: 1996 p. 351-428.

11. Mishin Y, Herzig C. Grain boundary diffusion: recent progress and future research [Internet]. Materials Science and Engineering: A 1999 Feb;260(1-2):55-71.Available from: http://linkinghub.elsevier.com/retrieve/pii/S0921509398009782

12. J.C.Fisher. . J. Appl. Phys 1951;22:74.

13. Wikipedia F. OSI Model [Internet]. System 2005;247-315.Available from: http://en.wikipedia.org/wiki/existensialism

14. Day JD, Zimmermann H. The OSI reference model [Internet]. Proceedings of the IEEE 1983;71(12):1334-1340.Available from: http://portal.acm.org/citation.cfm?id=202035.202039

15. Options C. The RS-232 Standard [Internet]. Instrumentation 2003;232-232.Available from: http://www.camiresearch.com/Data_Com_Basics/RS232_standard.html

16. Interface SP. Interface (SPI). Control 2009;(June):9509-9509.

17. Interface SP. Serial Peripheral Interface [Internet]. httpdewikipediaorg 2006;0153:10.Available from: http://de.wikipedia.org/wiki/Serial_Peripheral_Interface

18. Usb NI. USB I 2 C / SPI Interface. Exchange Organizational Behavior Teaching Journal 2000;3693(800)

19. Santos JP. Tecnologias de Accionamento e Comando [Internet]. 2010;[cited 2011 Feb 3] Available from: http://ims.mec.ua.pt/tac2010/

20. Ayala KJ. 8051 Microcontroller: Architecture, Programming, and Applications. Delmar Thomson Learning; 1999.

21. Sanchez J, Canton MP. Microcontroller programming: the microchip PIC. CRC; 2006.

22. Petroutsos E. Mastering Microsoft Visual Basic 2010. John Wiley and Sons; 2010.

23. Stepper motor [Internet]. [date unknown];Available from: http://www.cncroutersource.com/stepper-motor-drivers.html

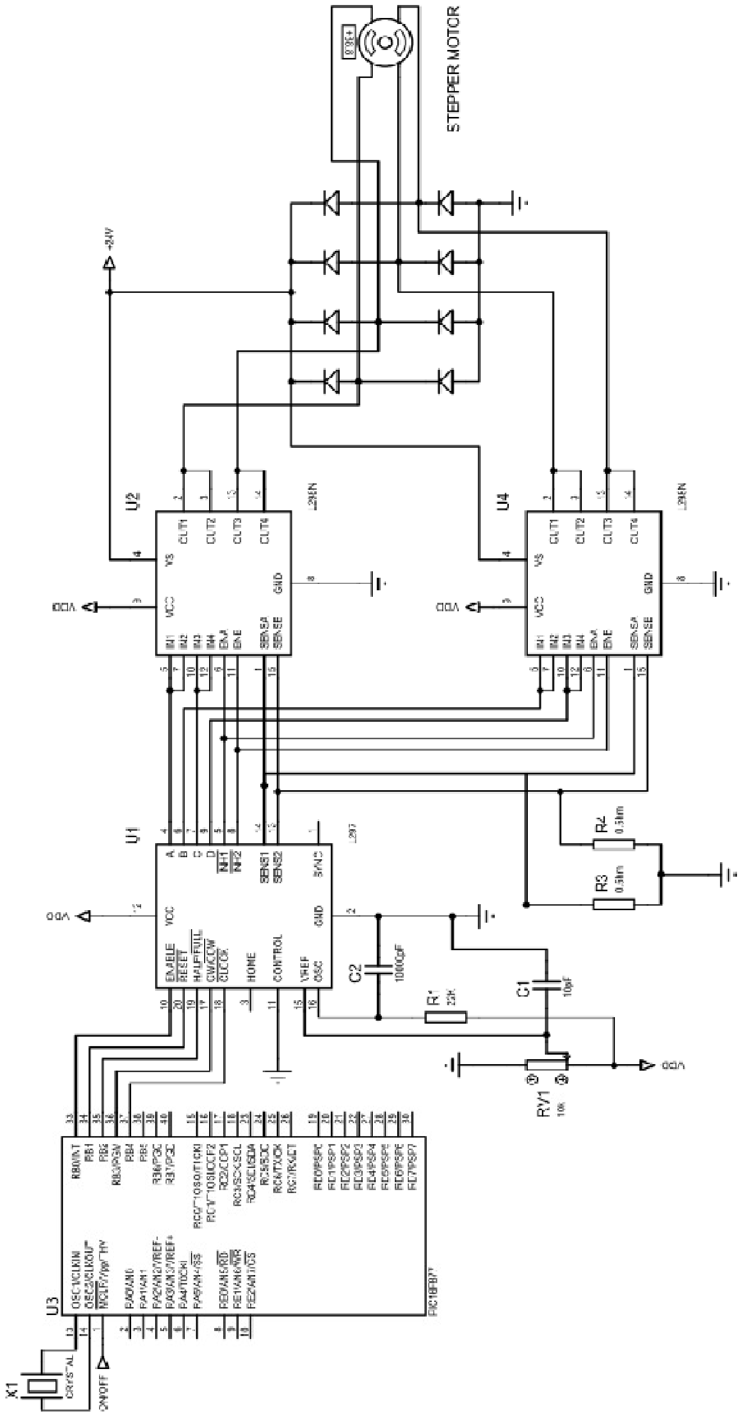
24. TI. Datasheet nema23 stepper motor [Internet]. 2000;Available from: http://sine.ni.com/ds/app/doc/p/id/ds-311/lang/en

25. Maxim. Max31855 Datasheet. 2011;

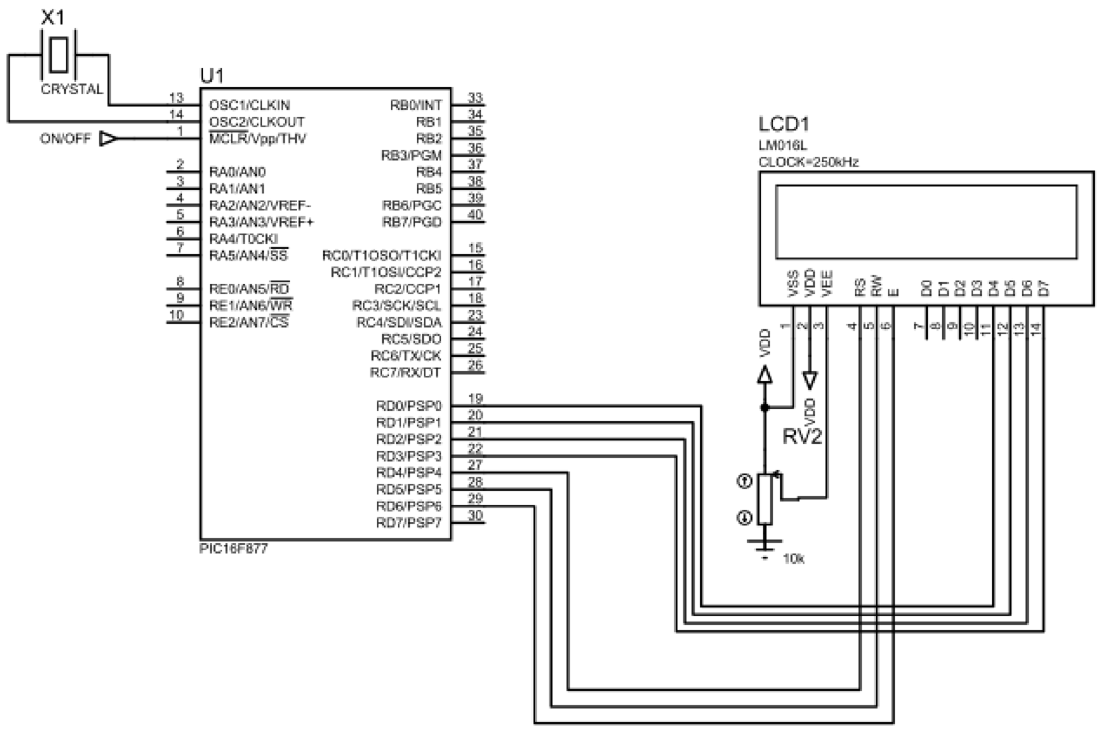
Annexes

Annex A - Analysis of the circuit

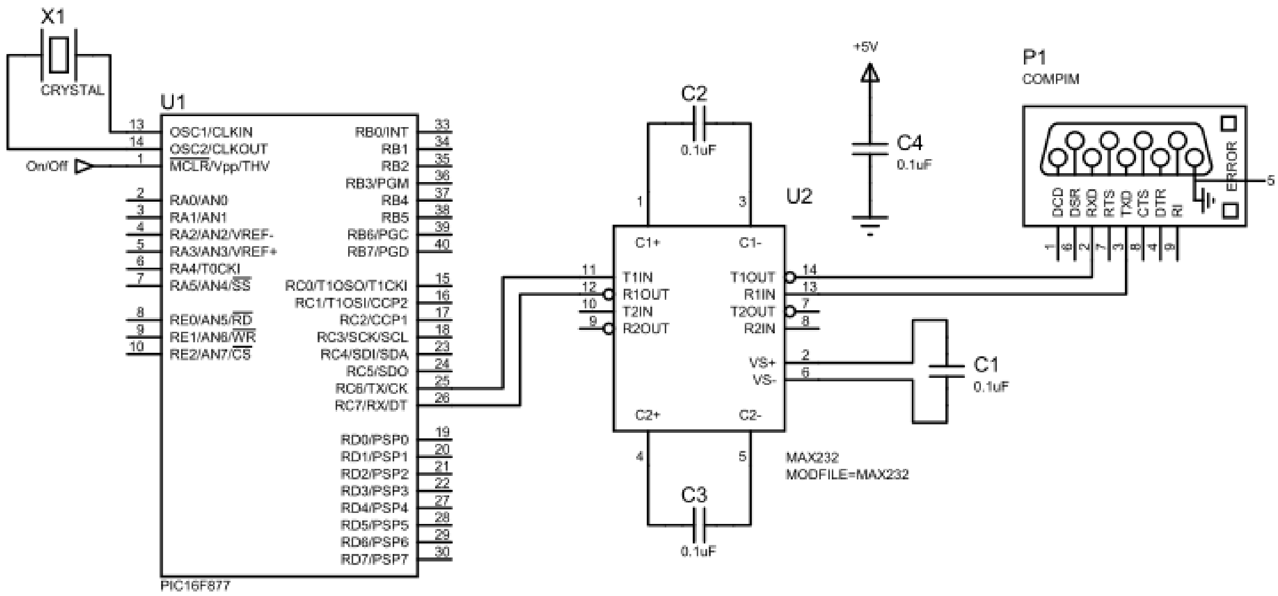
Motor circuit



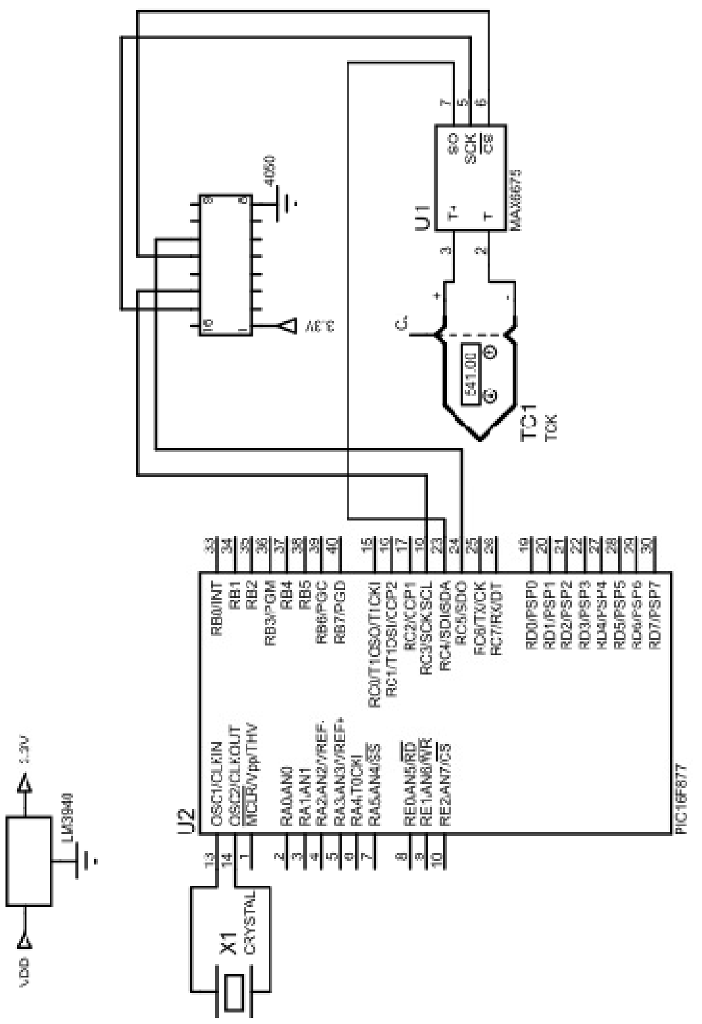
LCD circuit



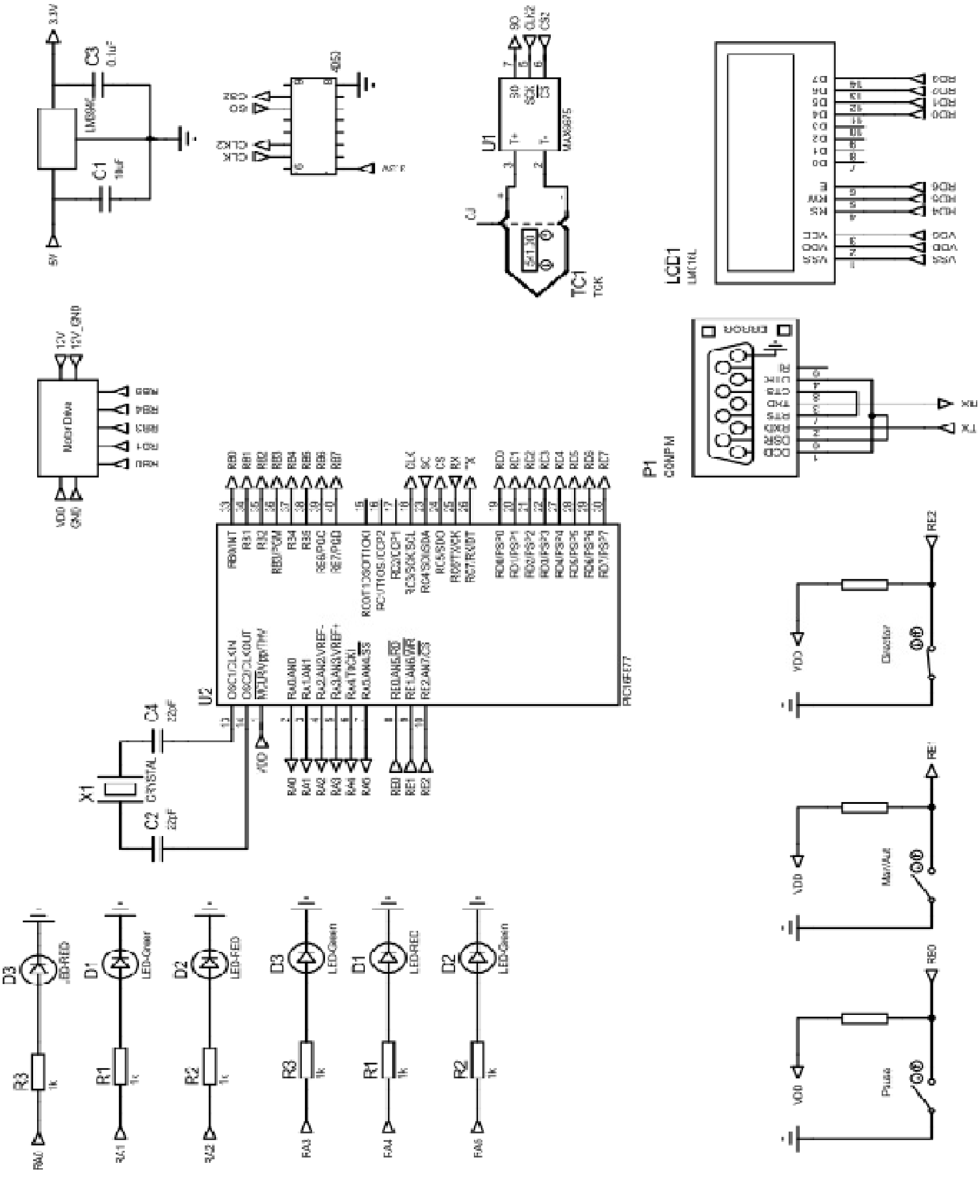
RS 232 circuit



Max31855 with 4050 level shifter



Electric circuit



Annex B- Program used in microchip (C Language)

File - Main.c

```
/**********************
Main.c
**********************/


#define _XTAL_FREQ 4000000
#include <stdio.h>
#include <htc.h>
#include "lcd.h"
#include "usart.h"
#include "max31855.h"
#include "delay.h"
#include "motor.h"
#include <stdint.h>



void display_value(short long value){
    short long value_x1000;
    short long digit;
    value_x1000 = (short long)(value * 100);
    digit = (value_x1000/1000000)%10;
    lcd_putch( '0' + digit);
    digit = (value_x1000/100000)%10;
    lcd_putch( '0' + digit);
//  lcd_putch( '.');     //decimal point
    digit = (value_x1000/10000)%10;
    lcd_putch( '0' + digit);
    digit = (value_x1000/1000)%10;
    lcd_putch( '0' + digit);
    digit = (value_x1000/100)%10;
    lcd_putch( '0' + digit);
    lcd_putch('m');
}
/***************************************************
                Pins
***************************************************/


/**********************
        Motor
**********************/

//PortB

/**********************
        Buttons
**********************/

//PortE
```

```
/***********************
        Leds
***********************/

//RA0 - ON
//RA1 - OFF
//RA2 - Man
//RA3 - Aut
//RA4 - Dir CW
//RA5 - Dir CCW

/***********************
        SPI
***********************/

//RE0 - ON/OFF
//RE1 - Man/Aut
//RE2 - Dir CW/CCW

/***********************
        232
***********************/

// RC6, RC7

/***********************
        LCD
***********************/
//PORTD

/***************************************************
                Variables
***************************************************/


unsigned int        input;
unsigned int        converter_ascii_to_dec;

void display_value1(short long value)
{
    short long value_x1000;
    short long digit;
    value_x1000 = (short long)(value * 100);
    digit = (value_x1000/100000)%10;
    lcd_putch( '0' + digit);
    digit = (value_x1000/10000)%10;
    lcd_putch( '0' + digit);
    digit = (value_x1000/1000)%10;
    lcd_putch( '0' + digit);
    digit = (value_x1000/100)%10;
    lcd_putch( '0' + digit);
}


void init_PORT(void){


// LEDS
```

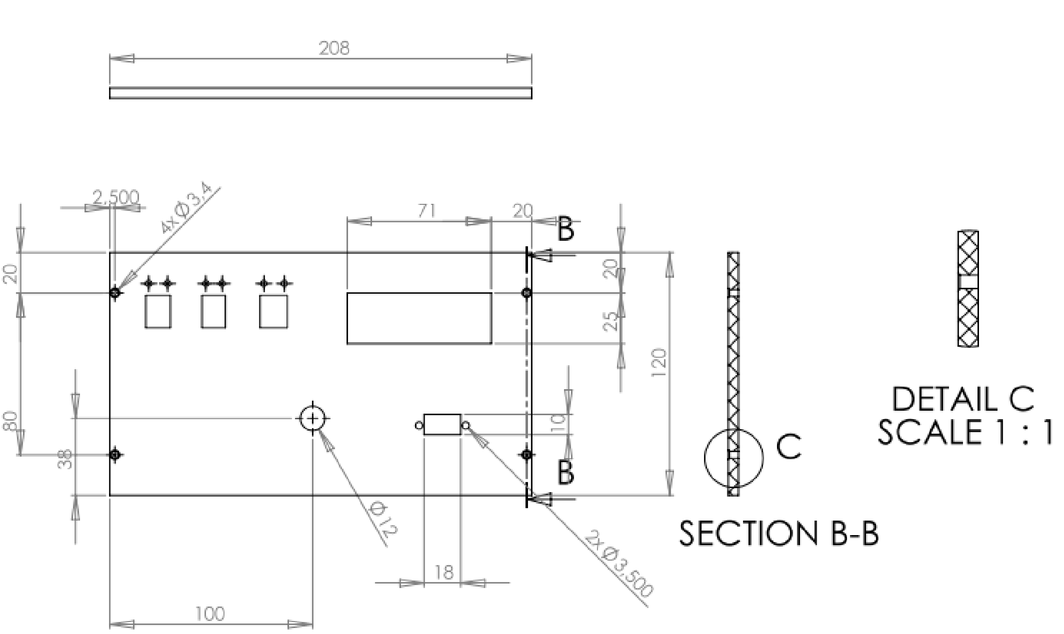
```
    TRISA0=0;
    TRISA1=0;
    TRISA2=0;
    TRISA3=0;
    TRISA4=0;
    TRISA5=0;


// Motor
    TRISB0=0;
    TRISB1=0;
    TRISB2=0;
    TRISB3=0;

    TRISB5=0;
    TRISB6=0;
    TRISB7=0;

// Buttons
    TRISE0=1;
    TRISE1=1;
    TRISE2=1;

    TRISC0=0;
}


void init(void){

    lcd_init(FOURBIT_MODE);
    TRISD=0;

}


void sendstring(void){
float temperature = readCelsius();
float temperature2=temperature*2;
int counter_real=motor_pos();
printf("U\n%04d%%%04f\nQ", Counter_real,temperature2);
tester=100;
}

volatile unsigned char outString[20];

void main(void){

    OpenSPI(SPI_FOSC_64,MODE_01,SMPEND);

    ADCON0 = 0x3C;
    ADCON1= 0x0F;
    CMCON = 0x07;

    init_PORT();
    init_comms();                // set up the USART - settings defined in
usart.h
    INTCON=0;                    // purpose of disabling the interrupts.
    lcd_init();                  // Lcd StartUp
```

```
while(1){

int max = 200;
    int i;
    for(i = 0; i < max;i++){
if (RE0 ==0){

RA0=1;
RA1=0;

    if (RE1 ==1){

RA3=0;
RA2=1;

        lcd_goto(0);                    // select first line in LCD
        lcd_puts("MAN.");           // display text in first line
        lcd_goto(0+4);                  // select first line in LCD
        lcd_puts("POS:");           // display text in first line
        lcd_goto(0x40);                 // Select second line
        lcd_puts("T1: ");           // display text in second line
        lcd_goto(0x47);                 // Select second line
        lcd_puts("|T2: ");          // display text in second line

        if (RE2 == 1){
RA4=0;
RA5=1;
            RB1=1;
            RB0=1;
            RB3=1;
            RB2=0;
            RC0=1;
            __delay_ms(1);
            RC0=0;
            __delay_ms(1);
            Counter_inter=Counter_inter+1;
            Counter_real=Counter_inter/40;
                    }                       // End RE2 On
        if(RE2 == 0)
            {
RA4=1;
RA5=0;

            RB0=1;
            RB1=1;
            RB3=0;
            RB2=0;
            RC0=1;
            __delay_ms(1);
            RC0=0;
            __delay_ms(1);
                    }                       // End RE2 0
                }                           // End RE1 1
    if (RE1 == 0){
RA3=1;
RA2=0;

        lcd_goto(0);                    // select first line in LCD
        lcd_puts("AUT.");           // display text in first line
```

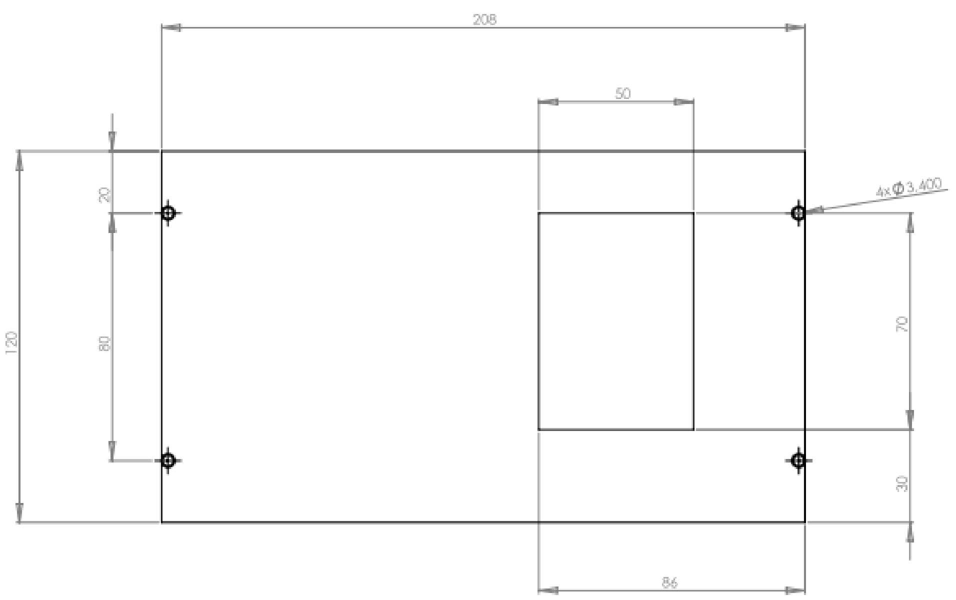
```
        lcd_goto(0+4);              // select first line in LCD
        lcd_puts("POS:");       // display text in first line
        lcd_goto(0x40);             // Select second line
        lcd_puts("T1: ");       // display text in second line
        lcd_goto(0x47);             // Select second line
        lcd_puts("|T2: ");      // display text in second line


        if(RCIF)    {                        // Receive Data 232
            input= getch();                  // read a response from the
user
            converter_ascii_to_dec=input-0x30;
                    }       // Conversion from Ascii to Decimal numbers
                    else
                    {
                    __delay_ms(1);
                    }
        if (converter_ascii_to_dec==2){
RA4=0;
RA5=1;
            RB0=1;
            RB1=1;
            RB3=1;
            RB2=0;

            RC0=1;
            __delay_ms(3);
            RC0=0;
            __delay_ms(3);
                                    }          // End input ==1
        if (converter_ascii_to_dec==1){

RA4=1;
RA5=0;
            RB0=1;
            RB1=1;
            RB3=0;
            RB2=0;
            RC0=1;
            __delay_ms(10);
            RC0=0;
            __delay_ms(10);
Counter_real=Counter_inter/10;
                                    }                     // End input
==2
        if (converter_ascii_to_dec==3){
RA4=0;
RA5=0;
            RB0=0;
                                        }                     // End
input ==3

}                                       // End RE1 Off
}                                   // End RE0
else
{
RB0=1;
RB5=1;
RB1=0;
```

```
__delay_ms(1);
}
}                                        //end While
setupMAX31855(ReadSPI);
sendstring();
lcd_goto(0);                    // select first line in LCD
lcd_puts("Encoder:");           // display text in first line
lcd_goto(0x40);                 // Select second line
lcd_puts("Tempera: ");          // display text in second line
    }
}
```

Annex C-Technical drawings of the control box

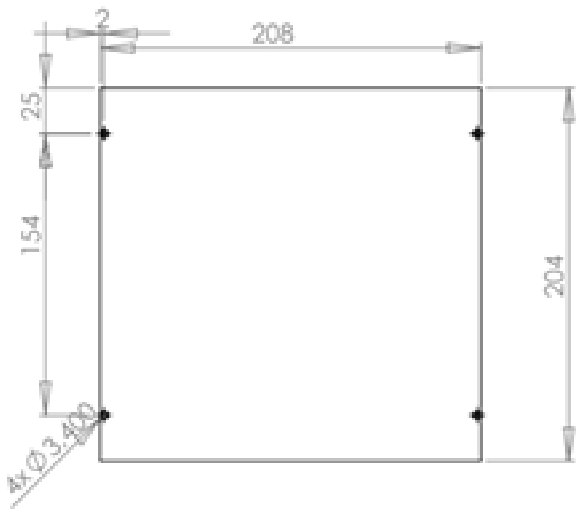


Front View

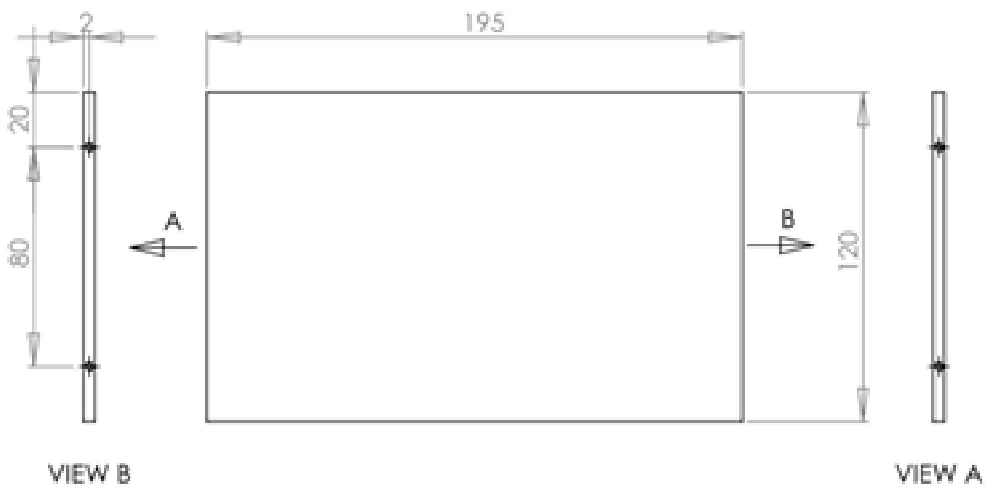


Back View

Cover



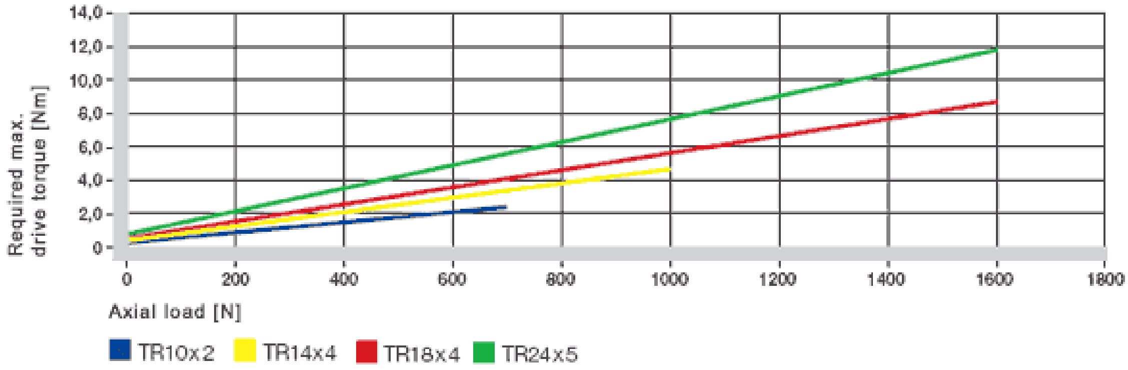
Cover

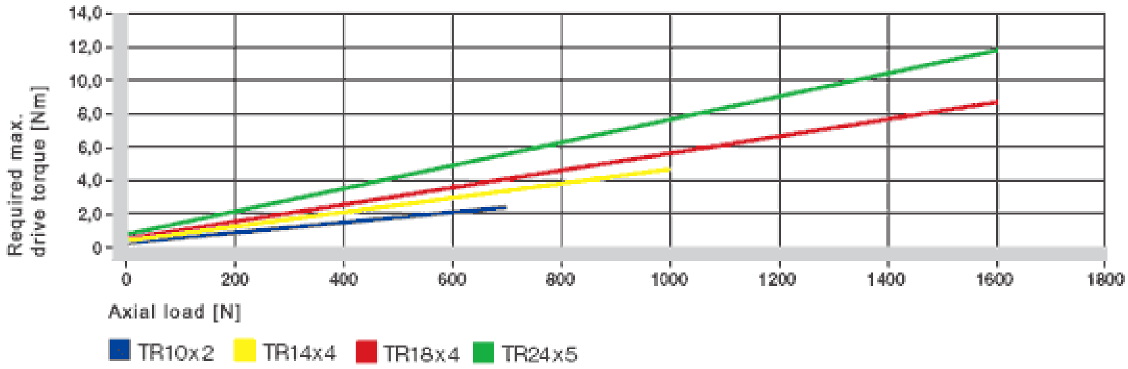


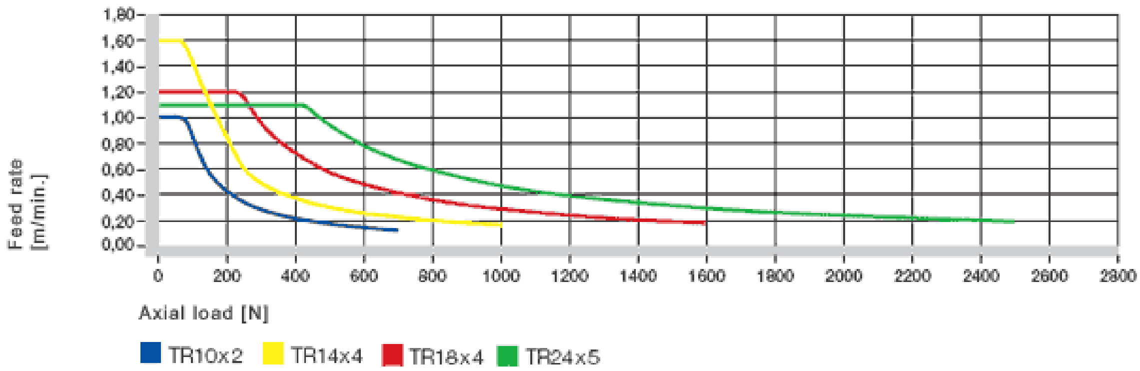
Sides

Annex D- Linear Table

Additional information







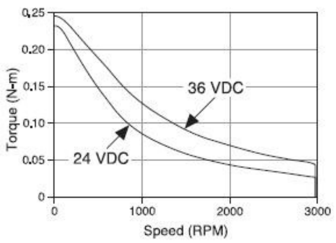
Annex E- Nema 23 Detailed Specifications

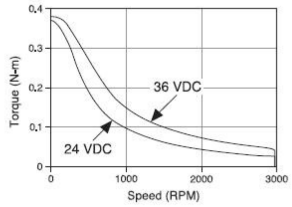
NEMA 17 Motor	
Electrical	
Step angle	1.8 deg
Steps per revolution	200
Angular accuracy	±3%
Phases	2
Industry Standards	
Industrial standards	CE, UR
Sealing standards	IP40
RoHS Compliance	Yes
Physical	
Operating temperature	-20 to 40 °C
Shaft load (20,000 hours at 1,500 rpm)	
Radial	15 lb (6.8 kg) at shaft center
Axial push	6 lb (2.7 kg)
Axial pull	15 lb (6.8 kg)
Recommended heat sink size	10 x 10 x 1/4 in. aluminum plate

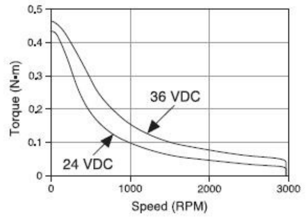
NI Part Number	**Manufacturer Part Number**	**Dual Shaft**	**Drive**	**Amps/Phase**	**Holding Torque oz-in. (N . m)**	**Rotor Inertia oz-in.-s^2 (kg-m^2 x 10^{-3})**	**Phase Inductance mH**	**Phase Resistance Ω ±10%**	**Detent Torque oz-in. (N . m)**	**Thermal Resistance °C/watt**	**Max Speed rpm**
780067-01	CTP10ELF10MAA00	no	P70530	1.0	43 (0.30)	0.0005 (0.0040)	7.7	5.25	1.98 (0.014)	6.21	3000
780068-01	CTP10ELF10MMA00	yes									
780069-01	CTP11ELF11MAA00	no		1.1	63 (0.44)	0.0008 (0.0050)	11	5.19	2.55 (0.018)	5.44	
780070-01	CTP11ELF11MMA00	yes									
780071-01	CTP12ELF10MAA00	no		1.0	80 (0.56)	0.0011 (0.0070)	12	6.51	2.97 (0.021)	4.71	
780072-01	CTP12ELF11MAA0	yes									

Torque versus Speed

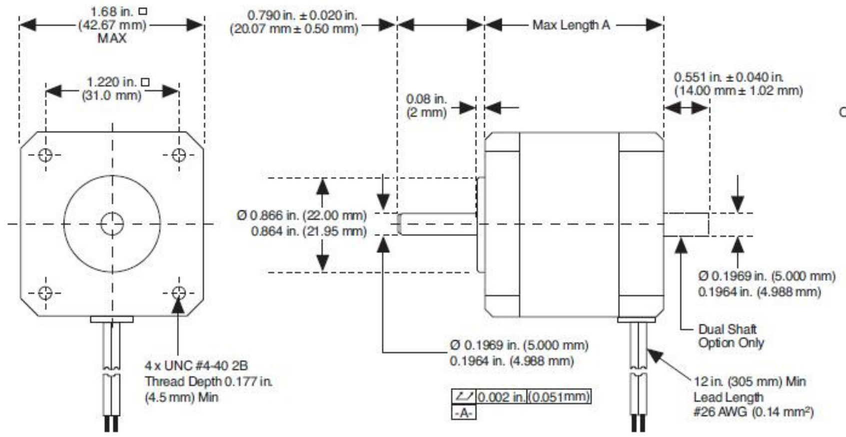
780067-01 and 780068-01	**780069-01 and 780070-01**	**780071-01 and 780072-01**
Torque versus Speed at 1.0 A	Torque versus Speed at 1.1 A	Torque versus Speed at 1.0 A

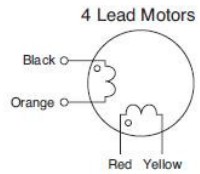






Dimensions and Wiring





Phase	Color
A-	Orange
A+	Black
B-	Yellow
B+	Red

NI Part Number	Manufacturer Part Number	Dual Shaft	Max Length A in. (mm)	Net Weight lb (kg)
780067-01	CTP10ELF10MAA00	no	1.37 (34.7)	0.441 (0.200)
780068-01	CTP10ELF10MMA00	yes		
780069-01	CTP11ELF11MAA00	no	1.61 (40.9)	0.573 (0.260)
780070-01	CTP11ELF11MMA00	yes		
780071-01	CTP12ELF10MAA00	no	1.92 (48.8)	0.750 (0.340)
780072-01	CTP12ELF11MAA0	yes		

NEMA 23 Motor

Electrical

Step angle	1.8 deg
Steps per revolution	200
Angular accuracy	±3%
Phases	2

Industry Standards

Industrial standards	CE, cUR, UR
RoHS Compliance	Yes
Physical	
Operating temperature	-20 to 40 °C
Rated ambient temperature	40 °C
Shaft load (20,000 hours at 1,500 rpm)	
Radial	20 lb (9.1 kg) at shaft center
Axial push	6 lb (2.7 kg)
Axial pull	50 lb (22.7 kg)
Recommended heat sink size	10 x 10 x 1/4 in. aluminum plate
Recommended encoder	780251-01